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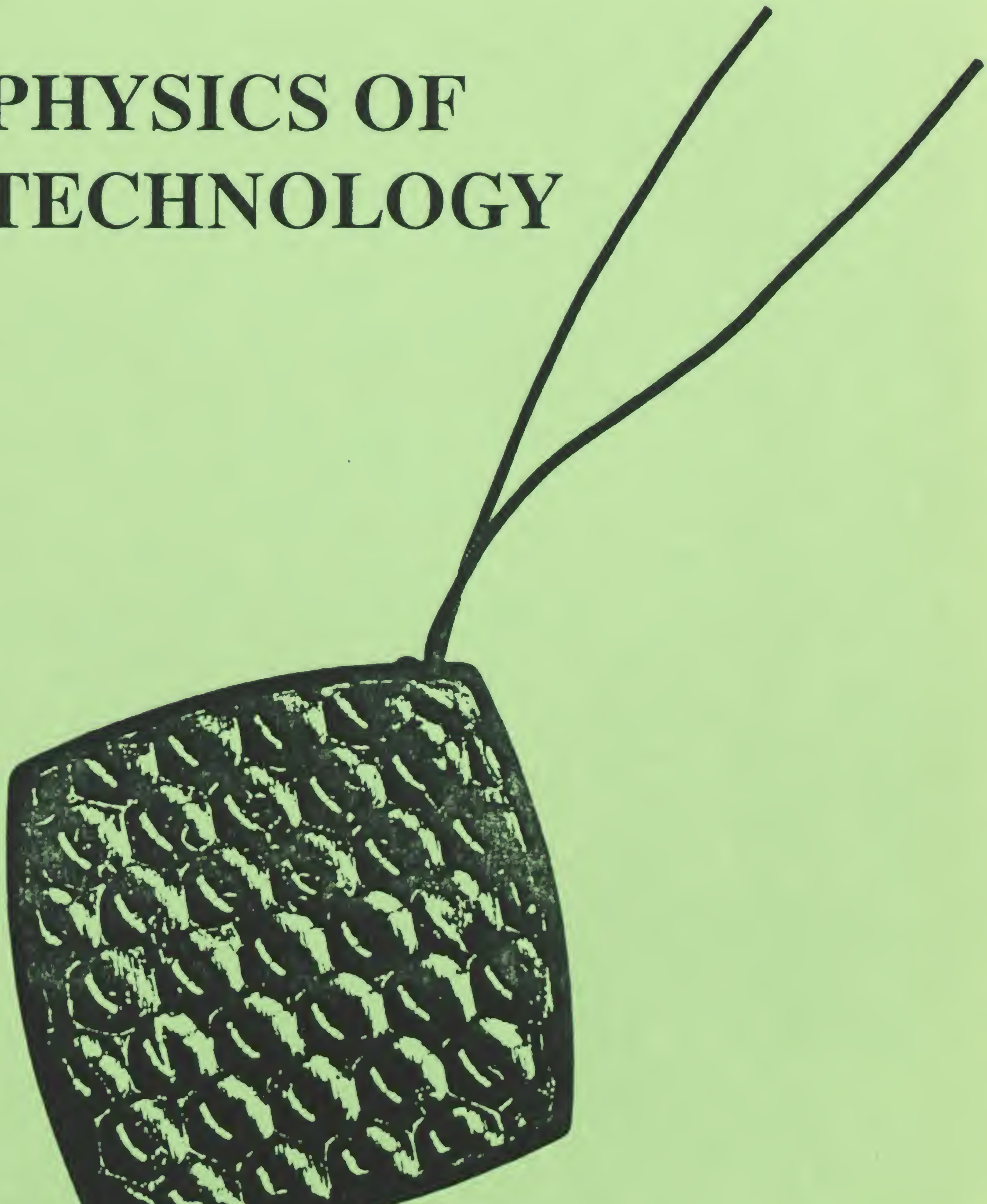
PHYSICS OF TECHNOLOGY



PUBLISHED BY AMERICAN ASSOCIATION OF PHYSICS TEACHERS

PHOTODETECTORS

THE INTERACTION OF LIGHT AND MATTER

PHOTODETECTORS

A Module on the Interaction of Light and Matter

TERC

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The Physics of Technology modules were produced by the Tech Physics Project, which was funded by grants from the National Science Foundation. The work was coordinated by the American Institute of Physics. In the early planning stages, the Tech Physics Project received a grant for exploratory work from the Exxon Educational Foundation.

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This module was written and tested at the Curriculum Development Laboratory of the Technical Education Research Centers, Inc.

The authors wish to express their appreciation for the help of many people in bringing this module to final form. The criticisms of various reviewers and the cooperation of field-test teachers have been most helpful. Several members of the staff of the Technical Education Research Centers also deserve special recognition for their contributions. They are:

Richard R. Lewis . . . . Apparatus Design
Mary A. Heffernan . . . . Graphic Composition
John W. Saalfield . . . . Illustration

In addition, special thanks go to our physics consultants:

Nathaniel H. Frank, Massachusetts Institute of Technology
Ernest D. Klema, Tufts University

Distributed by:
American Association of Physics Teachers
5112 Berwyn Road
College Park, MD 20740
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PREFACE

ABOUT THIS MODULE

Its Purpose

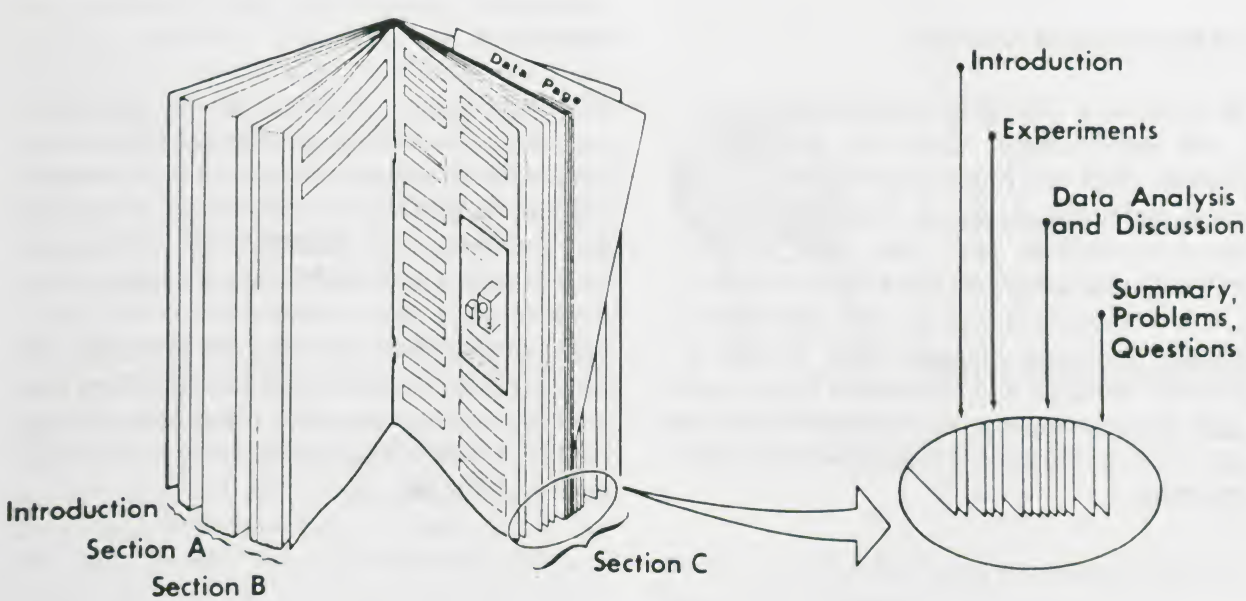
The purpose of the Physics of Technology program is to give you an insight into the physical principles that are the basis of technology. To do this you are asked to study various technological devices. These devices have been chosen because their operation depends on or illustrates some important physical phenomenon. In this module you will study several different photodetectors, devices which are sensitive to light. The behavior of each device uses a different kind of interaction between light and matter.

The PoT program has adopted a modular format with each module focusing on a specific kind of device. Thus you can select only those modules that relate to your own interests or areas of specialty. This preface highlights some of the features of the modular approach so that you may use it efficiently and effectively.

Its Design

The *Introduction* explains why we have selected photodetectors for study and what physical principles will be illustrated in their behavior. Learning *Goals* are given, as well as *Prerequisite* skills and knowledge you should have before beginning. The three *Sections* of the module treat different kinds of photodetectors. They are of increasing difficulty, but each can be completed in about one week.

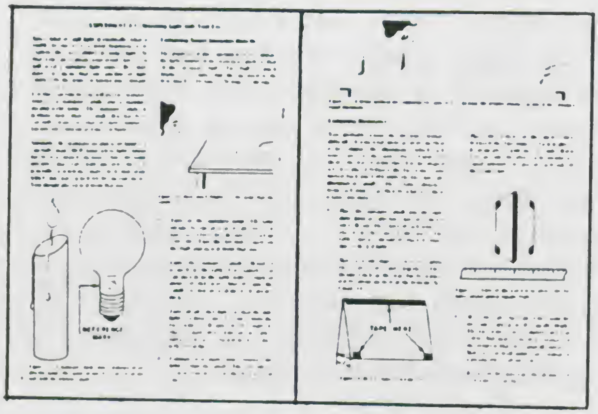
Each section begins with a brief *Introduction* to the topics treated and how they relate to the behavior of the device. The *Experiments* follow and take about two or three hours. Tear-out *Data Pages* are provided to record your data. The body of the section then describes the method of *Data Analysis*, including a *Discussion* of the physical principles which explain your results. A *Summary* ends the section with *Problems* and *Questions* you can do to test your understanding.



HOW TO USE THIS MODULE

To Begin

This module has been designed so that it can be quickly and easily scanned. That is, you can get the gist of the ideas and experiments by simply flipping from page to page, reading only the headings and italicized words, and looking at the illustrations. We suggest that, before you begin a section or an experiment, you scan through it in this way so you will know where you are going.

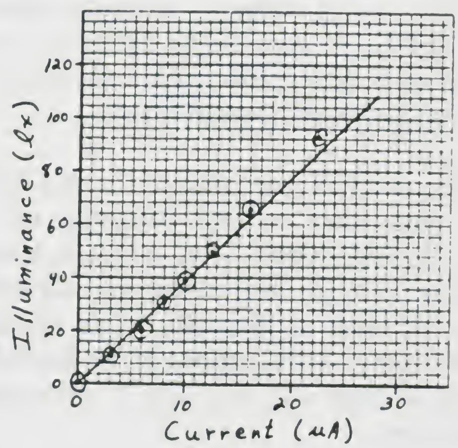


The Experimental Activities

The heart of a Physics of Technology module is the experimental study of the device behavior. This will often mean learning to use a new measuring device or instrument. Since your observations and data may not be analyzed until *after* you leave the laboratory, it is important that you do the experiments carefully and take accurate data. A scan of the Data Analysis and Discussion *before* you begin the experiment will help you to know what aspects of the experiment and data are important.

The Data Analysis

The data you take will generally have to be graphed before it can be analyzed. Graphing and graphical analysis are essential parts of experimental science. And understanding graphs is important for technology since technical information is often presented graphically. For these reasons, and since the discussion of your results will be centered around your graphs, it is important that you prepare them clearly and accurately.



Review

When you finish a section you should again scan it to be sure you understand how the ideas were developed. Reading the *Summary* will also help. Then you should try to answer the *Problems* and *Questions* to test your understanding and to be sure that you have achieved the Goals for that section. When you have completed the module, you may want to tear out certain pages for future reference; for example, conversion tables, methods of calibrating instruments, explanations of physical terms, and so on.

Photodetectors

Introduction: Why Study Photodetectors?

Photodetectors Use Important Physical Principles

In this module you will learn to use several of the most common detectors of light. Light (photo) detectors utilize important and interesting physics principles. Attempting to understand how these detectors behave will lead to some basic questions such as:

> What is light?
>
> What happens when light strikes something?

The answers we give will be somewhat brief and superficial. However, you should gain a good general knowledge of how photodetectors work and, equally important, how to use them.

The word photodetectors, as we will use it, means a device in which some electrical property (such as voltage, current, or resistance) changes when light strikes it. Following common practice, this definition arbitrarily excludes common light detectors such as photographic film. A more accurate title for the devices you will use might be "electronic transducers of electromagnetic radiation." But that is so technical that everyone prefers the simpler "photodetectors," even though it is a somewhat less accurate term.

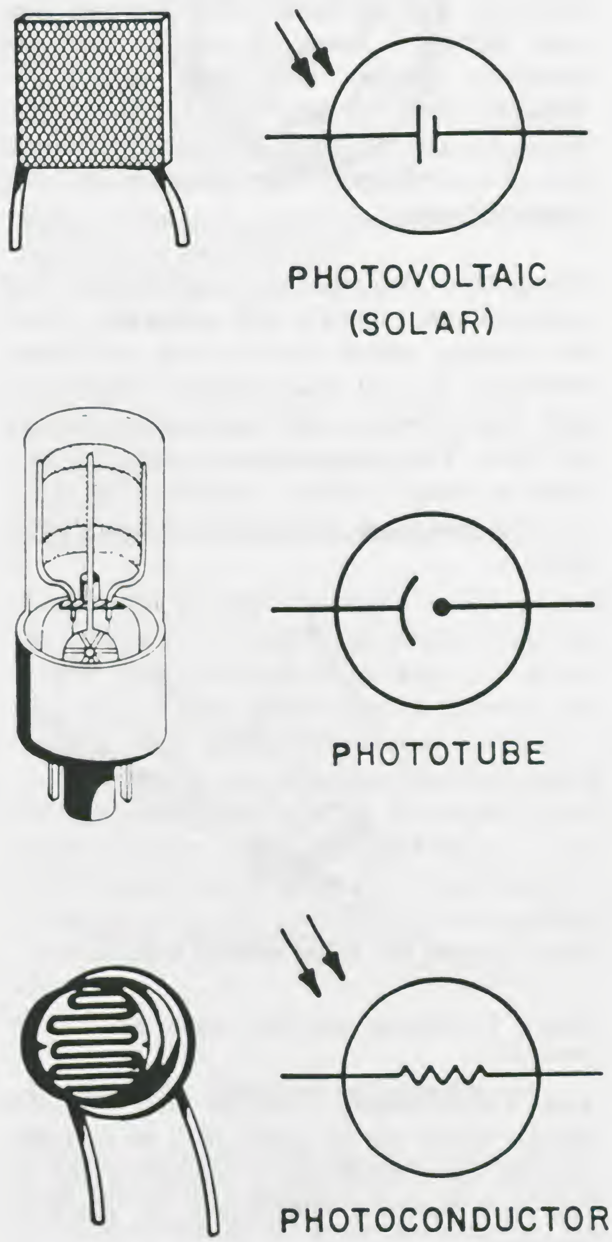


Figure 1. Photodetectors you will study in this module, and their schematic symbols.

The reason it is important to transform light into an electrical signal is that an electrical signal can be easily and accurately amplified, measured, and recorded. Since this module is not for an electronics course, you need not be concerned with how this is done, except in the most general way. The module instructions will show you how to build the electronics that you will need to measure current, voltage, or resistance.

Photodetectors Are Widely Used in Technology

Photodetectors have many applications in modern technology. They are useful because light, which they detect, can be sent over long distances, through small holes, and yet does not "disturb" things it strikes. You are probably familiar with light meters for cameras and "electric eyes" which open doors, but can you think of other applications for photodetectors? Two examples of such applications are:

Computers. Computer-card readers must read punched cards quickly and accurately. Cards are rapidly passed over a row of photodetectors, each of which registers whether or not it can "see" a light on the other side of the card. Thus the presence or absence of a hole is sensed without touching the card, thereby reducing wear and increasing reliability.

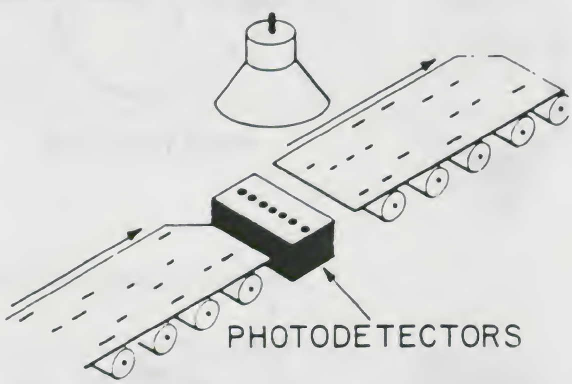


Figure 2. Reading computer cards with photodetectors.

Law Enforcement. A simple and effective burglar alarm can be made with an invisible infrared light beam and a photodetector. If the light beam is interrupted, an alarm is sounded.

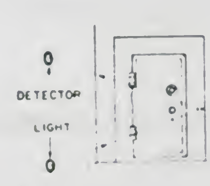


Figure 3. Burglar alarm systems sometimes use photodetectors.

The Physics Principles Have Many Applications

In order to understand the operation of photodetectors, you will investigate *photometry*, the measurement of light. You will also learn about the nature of light, of electrons, and of their interaction. Finally, you will learn about the nature of *semiconductors*—materials with electrical properties lying between those of conductors and insulators. While our coverage of these ideas will be far from complete, we will develop ideas which can be applied to other situations. For example:

Photometry. Astronomers can use the equations of photometry which relate distance and brightness to determine how far away certain stars are.

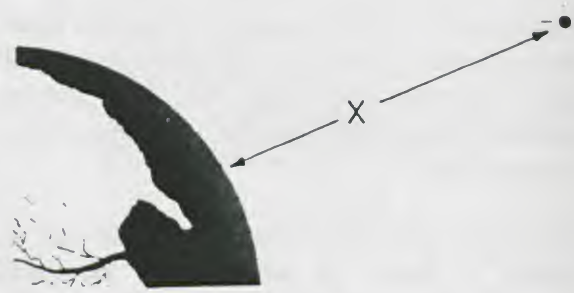


Figure 4. The principles of photometry are used to estimate the distances to stars.

Semiconductors. The same ideas needed to understand the operation of semiconductor photodetectors can be used to understand the operation of transistors and semiconductor diodes.

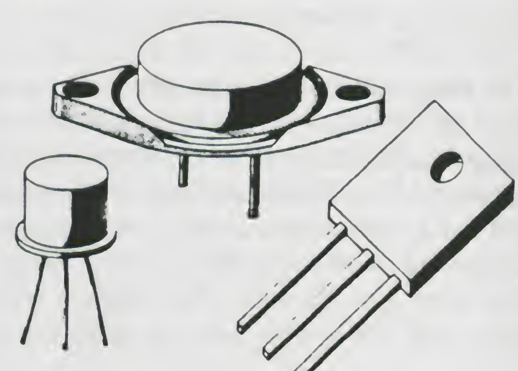


Figure 5. The principles of semiconductor photodetectors relate to much of modern electronics.

WHAT WILL YOU LEARN?

In the course of this module you will find several different kinds of topics presented. First, there are the different photodetectors (photovoltaic cells, phototubes, photoconductors). Each section is centered on a different type of detector so that you can gain experience in using each of the various kinds.

Next, there are the technical characteristics by which photodetectors are specified and compared. Each section concentrates on one or two of these characteristics so that you will understand the basis on which a particular detector can be evaluated.

Finally, there is the physical behavior on which each detector depends. In some cases this will reveal a law of physics, or the nature of some quantity, for example, light. In others it will simply be a picture or model by which we describe the observed behavior, for example, the model of conduction in semiconductors.

In the following we describe which of these topics is covered in each of the three sections.

SECTION A: Light Intensity and Illumination

The first photodetector you will study is the *photovoltaic* cell. This is the simplest of the detectors; it puts out an easily measured voltage when light shines on it. This photovoltaic "light meter" will be used to measure the relative *intensity* of two different light sources, a candle and an incandescent lamp. You will find that different photovoltaic materials measure the relative intensities differently. One agrees with your eye's estimates and the other doesn't.

You will also measure the photovoltaic output at various distances from a standard source. By applying the *Inverse Square Law of Radiation* you can determine the *linearity* and *sensitivity* of your photovoltaic light meter. In an optional experiment you can see how photovoltaic cells can be used as *solar cells* to generate electrical power.

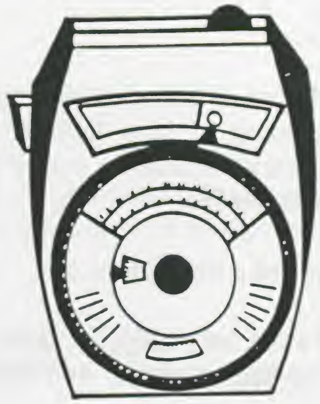


Figure 6. The photographic light meter is a common application of photodetectors.

SECTION B: Spectral Characteristics

In Section B you will measure the *spectral sensitivity* of an older type of photodetector, called a *phototube*. This type of photodetector is now rarely used in modern electronics. But from its response to light of various colors, you will learn about the nature of light itself. You will see that light in some circumstances can be thought of as a *wave* and in others as a lot of tiny "particles" that interact with the electrons of the material they strike. This is called the *particle model* for light.

SECTION C: Light and Semiconductors

Finally, you will evaluate the *response time* and the *thermal stability* of a third type of photodetector, called a *photoconductor*. This device, like the photovoltaic cell, is a *solid-state* device. From its behavior you will learn about the structure of *semiconductors* and why they have the particular conductive properties they do.

You will also have an opportunity to build a simple burglar alarm, using a photoconductor, as an example of control systems that use photodetectors.

GOALS

The general goal of this module is to give you an understanding of how light is measured and the physical principles on which these measurements depend.

This will involve a knowledge of:

How to use and relate the quantities that measure light intensity and illumination.

How to use three common light detectors (photovoltaic cells, phototubes, and photoconductors) to measure light.

The physical phenomenon on which each detector depends, including the photoelectric effect and electron-hole production in semiconductors.

The physical descriptions of these phenomena and how they can be used to predict, approximately, properties of photodetectors, such as spectral sensitivity, temperature effects, response time, and linearity.

At the end of this module you should be able to demonstrate your understanding of these goals by doing the following:

Section A

1. Measure the current and electric power produced by a photovoltaic detector as a function of incident light intensity.

2. Mathematically relate illumination, intensity, and distance in order to calculate the value of any one, given values for the other two.

3. Given photovoltaic cell specifications, choose appropriate detectors for typical applications such as solar cells and light meters.

Section B

4. Describe and measure the spectral sensitivity of any photodetector.

5. Describe the simple wave and particle models of light and give evidence for each.

6. Relate a model of light and light-electron interactions to the operation of photoemissive detectors.

7. Describe, or be able to perform, an experiment using a phototube to determine ϕ, the photocathode work function.

Section C

8. Perform experiments to measure the response time of a photoconductor and the temperature dependence of the dark current of a photodiode.

9. Describe a model of conduction in semiconductors, and apply this model to photoconductors in order to predict their properties, including response times.

10. Predict the value of the energy gap from dark current data, and use this to predict the long-wavelength cutoff for photodiodes.

PREREQUISITES

The following concepts will be used in this module. If you do not have a good understanding of them, you may have trouble with the material in the module. If in doubt, ask your instructor.

1. *Ohm's Law:* A familiarity with electric current, voltage, and resistance, as well as Ohm's law and the calculation of electrical power, will be assumed.

2. *Oscilloscope:* You should be able to operate a simple oscilloscope. You may learn to do this from the Appendix at the back of the module.

SECTION A

Light Intensity and Illuminance

WHAT MAKES A GOOD LIGHT DETECTOR?

If you were given a blank check and told to go out to buy the best light detector money can buy, what would you look for? Take a moment to try to list as many properties as you can which would characterize a "good" light detector. To help in your thinking, consider various conditions for which you might want an accurate measurement of the amount of light present.

Some of the properties that should be on such a list are the following:

Sensitivity

Under some conditions (at night, for example) there is very little light. But you would still want the photodetectors to indicate the amount present. Thus the photodetector should be very *sensitive*, giving accurate readings down to very low light levels.

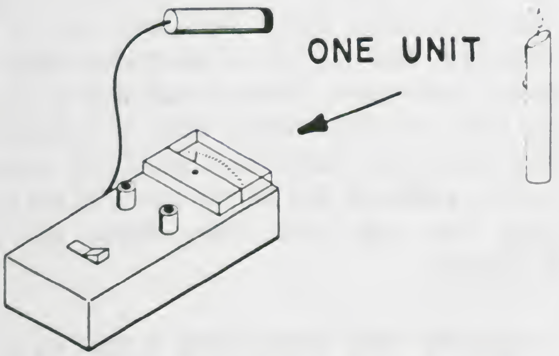


Figure 7. The photodetector should be sensitive to small amounts of light.

Linearity

Whatever the response to the light is, if the amount of light doubles, then the detector's response should also double. In other words, the response of the detector should be proportional to the light intensity. Another way of saying this is that the response should be *linear* with the light intensity. This means that a graph of the photodetector's response versus the actual light level is a straight line.

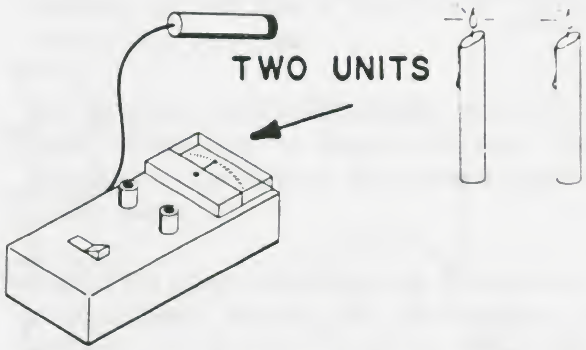


Figure 8. When the amount of light doubles, the output of the photodetector should also double.

Spectral Sensitivity

The response of a photodetector should not depend on the color of light that illuminates it. It should be the same for the same amount of light, regardless of whether the light is green or red or whatever. The detector's response to various colors is called its *spectral sensitivity*. A good photodetector has a *flat* spectral sensitivity. That is, a graph of its response against various colors of light incident on it is a straight, "flat" line.

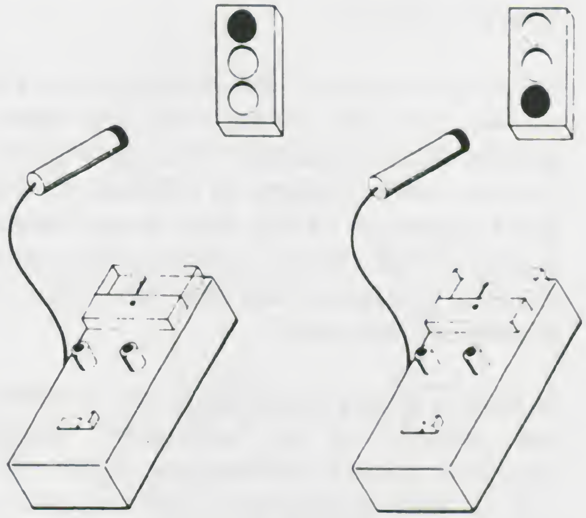


Figure 9. The color of the light source should not matter.

Response Time

No matter how fast the light intensity changes, the detector should be able to keep up. Unfortunately, some detectors take many seconds to reach a new reading after the light level has changed. This slow response is not satisfactory for many applications; good photodetectors have very short *response times.*

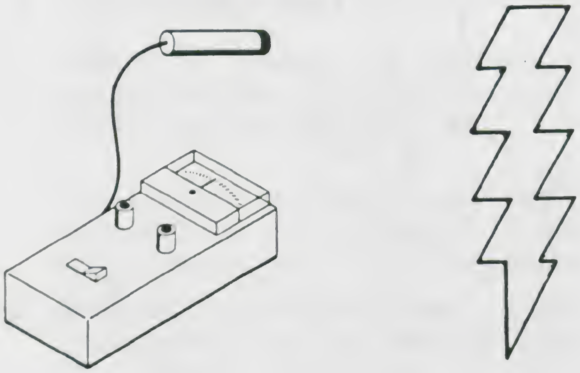


Figure 10. As the light level changes, the detector should be able to keep up.

Thermal Stability

An ideal photodetector should be unaffected by changes in its temperature. Some photodetectors, however, are quite temperature sensitive. That is, their responses may *drift* if the temperature changes, even though they "see" the same light level. (See Figure 11.)

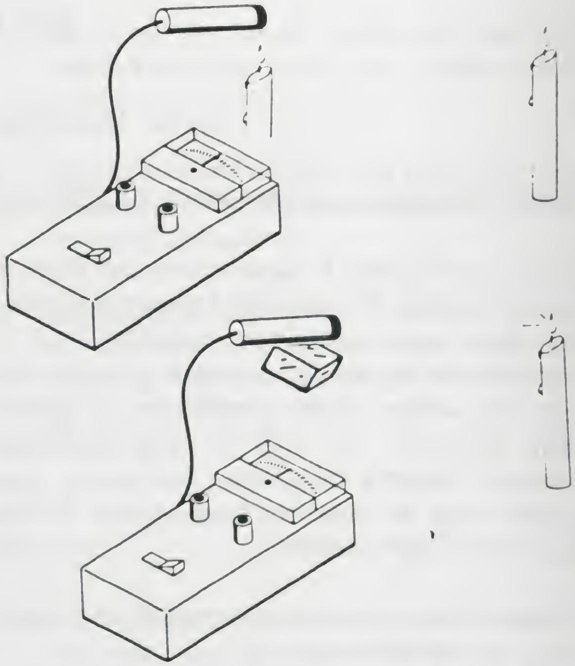


Figure 11. Temperature should not affect the detector reading.

Your Experiments

During the course of your experiments in this module, you will evaluate the five characteristics listed previously for a good photodetector, using a variety of different devices. The explanations of why these devices behave as they do will reveal a number of important physical principles that are the basis of modern *optoelectronics.*

In Section A you will evaluate the *sensitivity* and *linearity* of a "solid-state" photoconductor called a *photovoltaic* device. You will see how photovoltaic cells are used to measure light in light meters and to convert light power to electrical power. When used in this way, they are called "solar cells."

MEASURING LIGHT

To begin to understand photodetectors, you must first learn about light and how it is measured. The science of measuring light is called *photometry.* What we call light is what our eyes see. Many related kinds of radiation, such as infrared, ultraviolet, and radio waves, are not visible to the human eye and are not light. You will learn more about this in Section B.

A problem with photometry is that its language is complicated. Many different terms are used to describe slightly different things. To make things worse, several different measurement units are used for each term. In this section we will try to make some sense out of this confusion.

Intensity and Illumination

First, it is important to distinguish between the *intensity* of a *light source* and the amount

of *illumination* falling on an *object*, such as a photodetector. When you move away from a light source, it appears that the light is getting less intense. But you know that its output does not decrease as you move away. What happens is that less light falls on your eyes.

We will use the term *luminous intensity I* as a measure of the strength of a source independent of the detector location. The word luminous simply indicates that we are referring to light intensity, rather than, say, sound intensity.

We will use the term *illuminance L* for the amount of light falling on a *unit area* of an object. As the area of an illuminated object increases, so does the total amount of light it receives. As the distance from the source changes, the illuminance changes.

An Example

An example may help clarify the concepts. Figure 12 illustrates three light sources of different intensities. A light detector at the same distance from each shows that the illuminance is greater for the higher intensity lights. Thus the *illuminance increases as the intensity of the source increases if the distance is held constant.*

The brighter sources are seen to produce the same illuminance at larger distances. Thus *illuminance decreases as the distance from the source decreases.*

One of the goals of Section A is to understand how intensity, illuminance, and distance are related. The relation between these three quantities is the foundation of photometry.

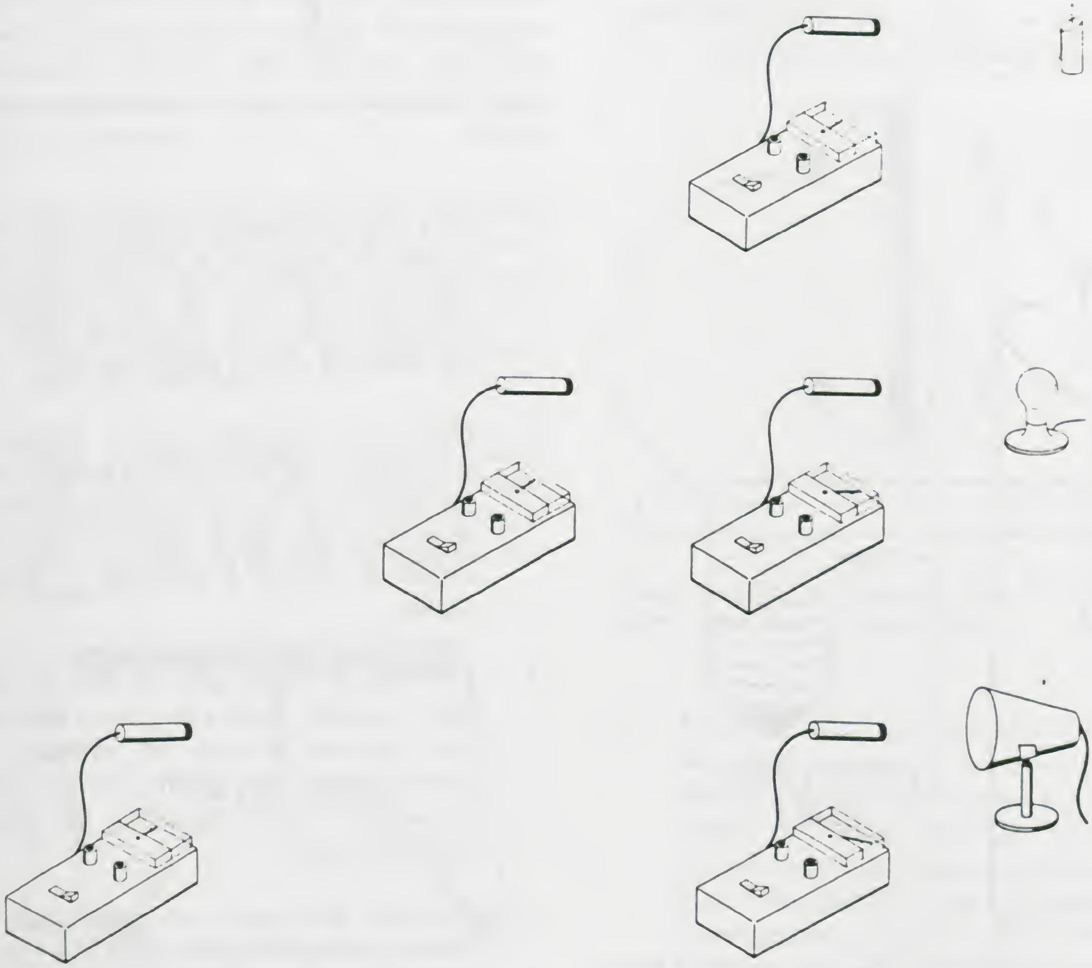


Figure 12. Three sources of increasing intensity produce the same illumination at increasing distances.

Since what we call light is essentially what is visible to our eyes, a good beginning is to explore the eye's ability to judge light. So that you can evaluate your results later, you will need a *standard* light source. By "standard" we mean that the amount of light emitted by the source is known and constant.

For this experiment you will use two standard sources, a standard candle and a standard incandescent lamp. The standard candle is nothing more than a candle that has been carefully made, so that its light output is known and constant as long as it burns.

Similarly, the standard incandescent lamp is a carefully made 40-W lamp whose light output has been accurately measured. Since the lamp intensity may vary with direction, there is generally a reference mark on it indicating which side was viewed for the measurement. You should also view it from that side.

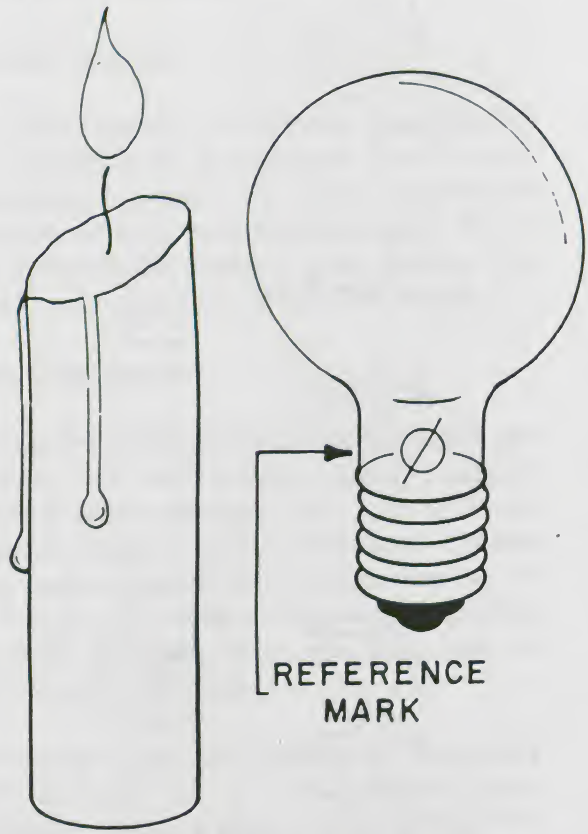


Figure 13. A standard candle and a standard incandescent lamp. The lamp should be viewed from the side with the reference mark.

Comparing Source Intensities Directly

The purpose of this experiment is to compare the light output of the standard candle to that of the standard lamp. The lamp is much brighter, of course, but the question is, by how much. . .10 times? 20 times? 100 times?

Figure 14. How much brighter is the lamp than the candle?

1. *Turn on the standard lamp.* The lamp should be operated at its specified voltage, say 110 V AC. Be sure it is set up correctly. Find the reference mark on the bulb and view it from that side.

2. *Light the standard candle.* Mount it securely to the table. For example, you can stick it to the table with a couple of drops of hot wax. Also be sure the candle is not in a draft so it doesn't flicker.

3. *Turn off all other lights* so that the only light reaching your eye comes from the two sources. It may be necessary to place a dark drop cloth on the table's surface or as a backdrop to reduce reflected light.

4. *Estimate how many times brighter the lamp is than the candle.* This can only be a guess, but try to do the best job you can.

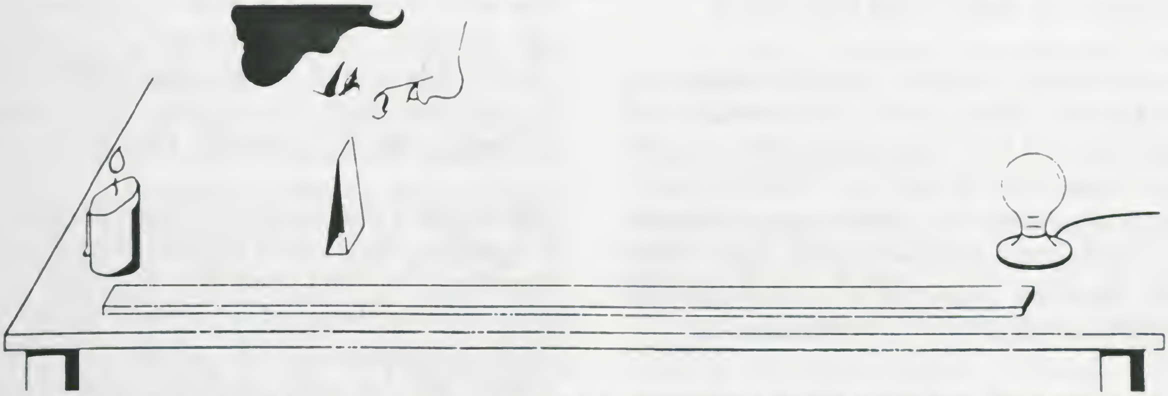


Figure 15. A better method for comparing two sources is to measure the relative distances at which they produce equal illuminance.

Comparing Illuminance

You probably found the previous estimate difficult. A somewhat more accurate method is to compare the illuminance which each source gives to the same object. Figure 15 shows one way of doing this. A wedge-shaped screen is placed between the two sources and moved back and forth until the two sides are *illuminated equally.* The relative distances from each source can then be related to their relative intensities.

5. *Place the standard candle and the standard lamp at opposite ends of a meter stick.* Be sure the *center* of each source is placed at the end of the stick. The table's surface should be black to minimize reflected light.

6. *Make a wedge-shaped screen* by taping two 5-in × 7-in cards together. They should touch at the top, but be separated by about an inch at the bottom. See Figure 16.

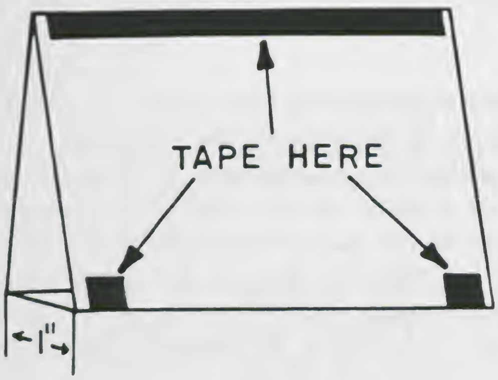


Figure 16. How to make a viewing screen.

7. *Place the screen on the meter stick* between the two sources. View it *directly from above* with *one eye* only. When you are directly above, you should see equal amounts of card on each side of the center line.

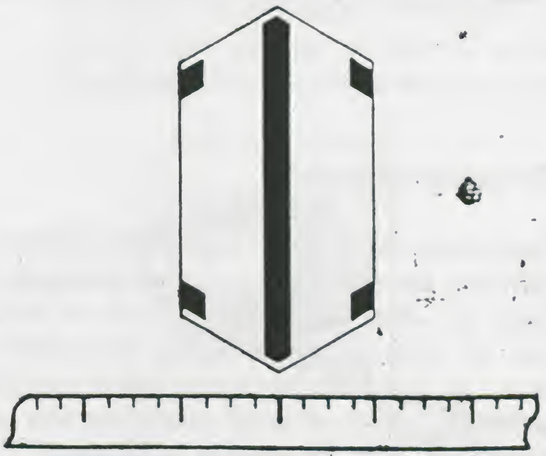


Figure 17. View of the screen from above. The two halves should appear equally bright.

8. *Move the card back and forth* until the two sides appear to be equally bright. The two sources are of slightly different colors, but make your best estimate of the position that gives *equal illuminance.* Make several trials until your estimate is reproducible to about 1 cm.

9. *Record in the data page the distance* of each source from the screen.

ABOUT THE PHOTOVOLTAIC CELL

The first photodetector you will investigate is a solid-state device called a *photovoltaic cell.* (See Figure 18.) Its name comes from the fact that when light strikes it, a voltage appears across its terminals. Similar photodetectors are often found in photographic light meters and are also "solar cells," which produce electrical power directly from light.

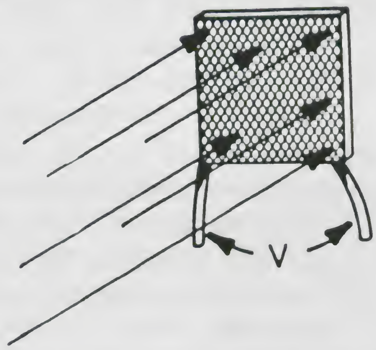


Figure 18. A typical photovoltaic cell. When light strikes the surface, a voltage appears across the wires.

Photovoltaic Materials

Photovoltaic cells can be made of a number of different materials. The two most common of these are *selenium* and *silicon*, each of which has its own special properties and applications. In the following experiments you will investigate some of these properties and see how they lead to specific applications for each type of photovoltaic cell.

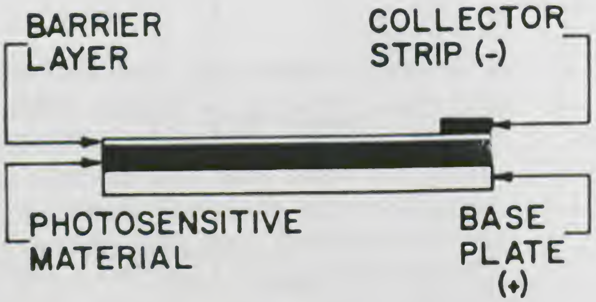


Figure 19. Cross section of a photovoltaic cell. The photosensitive layer can be either selenium or silicon.

The photovoltaic cell is made by sandwiching the sensitive material between a so-called "barrier" layer and a base plate, which serves as an electrical connection. The voltage appears across the sandwich. (See Figure 19.)

The detailed explanation of how this happens is based in the theories of *solid-state* physics, the study of solid materials. Some of these ideas will be discussed in Section C. But for these experiments, simply consider the photovoltaic cell for what it does: it produces a voltage when light strikes it.

Illumination and Electric Current

In spite of its name, the photovoltaic cell can be more easily understood as a source of electric current than as a voltage source. Of course, voltage and current are related by Ohm's law. If the photovoltaic cell is connected in series with resistance R (Figure 20), then the current I for a given photovoltaic voltage V is:

$$I = \frac{V}{R}$$

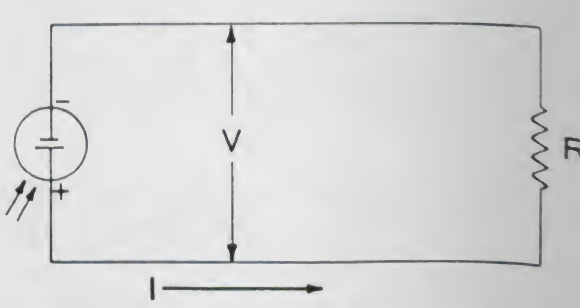


Figure 20. In a circuit, the photovoltaic cell acts as a light-energized current source.

The resistance of the circuit is an important factor in determining the photovoltaic characteristics, as you will see in Experiment A-3. For a given circuit resistance, however, the size of the current depends on the amount of light falling on the cell; the more intense the illumination, the larger the current. In effect, the photovoltaic cell converts light "current" into electrical current.

The purpose of this experiment is to give you some familiarity with the photovoltaic cell as a detector of light. To analyze the current produced by a photovoltaic cell, simply connect it to a sensitive ammeter, with a range of 0 to 100 microamperes (μA). The circuit resistance of Figure 20 will then be the internal resistance of the meter itself. This is generally about 1000 ohms (Ω). You should have both the silicon and the selenium types of photovoltaic cell available.

Observing Photovoltaic Behavior

1. *Examine your photovoltaic cell.* Look carefully at the cell's surface.

   CAUTION: *Do not touch the surface since it is delicate and can be easily damaged.*

   Note how the wires are connected to pick up the current.

2. *Connect the photovoltaic cell to a 0- to 100-μA ammeter* (Figure 21), and explore how the current changes as the amount of light falling on the cell changes.

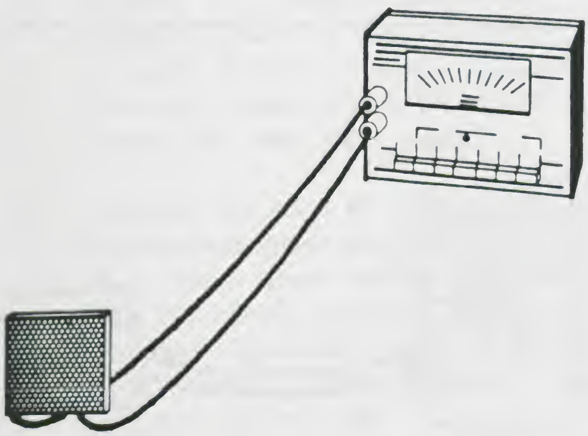


Figure 21. Connect the photovoltaic cell to a 0–100-μA ammeter and observe how the current changes with illumination.

3. *Compare the selenium cell with the silicon cell.* What differences (if any) can you determine? Recall the characteristics of a good photodetector discussed in the introduction.

Making It "Directional"

In many applications you need to measure the light coming from only one direction. In photography, for example, the light meter should measure only the light reaching the camera from the subject. It should not be sensitive to light coming from other directions. To achieve this, you must shield the detector from this "stray" light. A simple technique is to put the photodetector in a "light-tight" box with a hole in it. Then the detector responds only to light coming from the direction toward which the hole is pointing.

4. *Mount your cell rigidly in a light-tight box.* (See Figure 22.) The hole should be slightly larger than the photovoltaic cell and the inside of the box should be blackened to minimize reflections. You should also provide a way of making electrical connections to the cell wires.

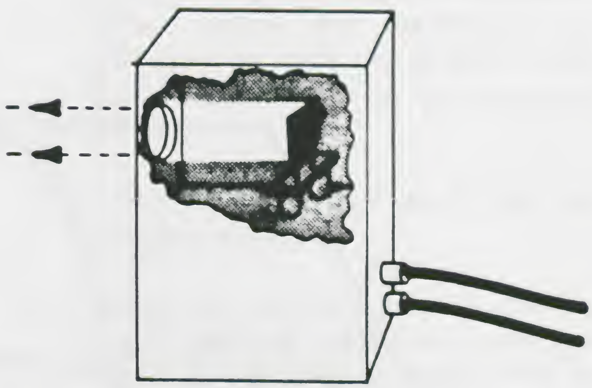


Figure 22. Mount the photovoltaic cell inside a blackened box so it detects light from only the direction toward which it is pointed.

5. *Connect the photovoltaic cell to the meter* as before and investigate its *directionality.* Point it at a bare light bulb, for example, then turn it slightly. Over what angle does the photodetector "see" the light source?

EXPERIMENT A-3. Measuring Light with a Photovoltaic Cell

What you have constructed in Experiment A-2 is essentially a directional light meter. It is equivalent in almost every respect with what is sold for photography and for many other purposes. The only thing lacking is *calibration*, which relates your meter reading to the actual amount of light striking the photovoltaic surface.

Calibration of your light meter will be done in Experiment A-4 and the discussion on photometry following. However, even without calibration, you can use your light meter to compare relative intensities of two light sources just as you used your eye in Experiment A-1.

Again you can do this in two ways, one of which we shall call the *direct method*, and the other we shall call the *equal-illumination method*. In the direct method, you mount the photovoltaic cell at the same distance from each of the two light sources and compare the meter readings produced. In the equal-illumination method, you determine the distance from each source which produces the same meter reading.

Setting Up the Experiment

1. *Set up the components*, as illustrated in Figure 23, in a relatively dark room. Initially use the *selenium* photovoltaic cell as the detector and the standard *40-W lamp* as the source. Be sure the lamp's reference mark points toward the detector.

2. *Carefully align the photovoltaic cell.* Two conditions must be met if your results are to be accurate:

   a. The photocell must see *only* the light from the source. Look for stray light and block it out. If light is being reflected from the table's surface, cover it with a black material.

   b. The photocell must see the *entire* light source. Thus the box must be aimed *directly* at the source. Rotate the box back and forth about a vertical axis to find the maximum deflection of the meter.

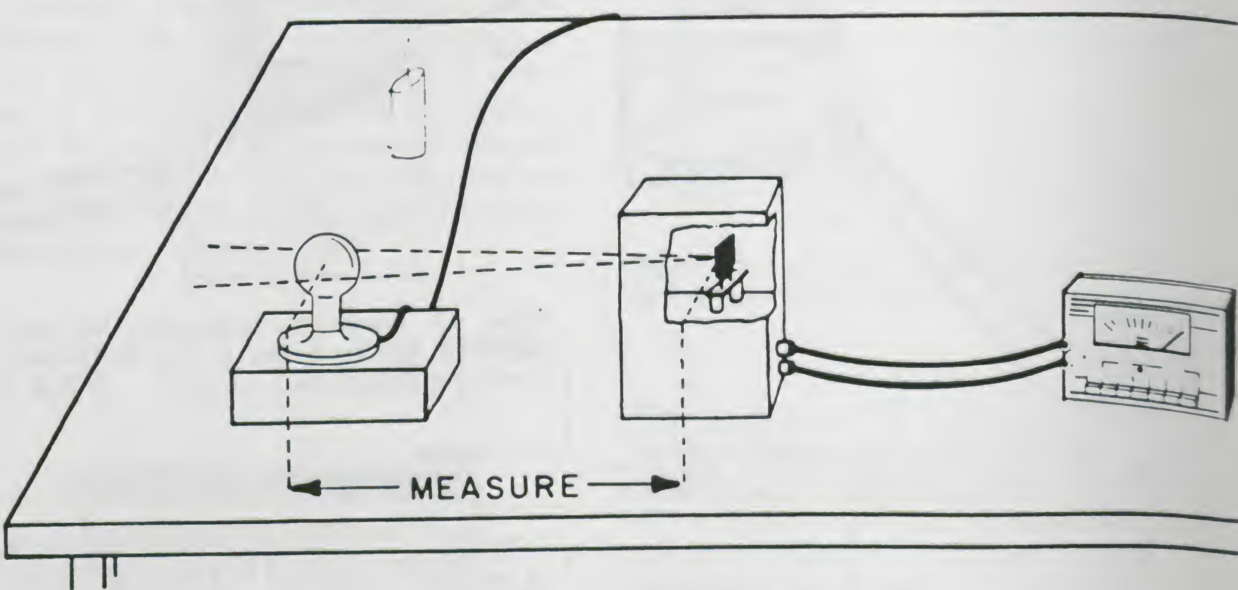


Figure 23. The photovoltaic light meter can be used to compare the relative intensities of two light sources. However, in doing so one makes certain assumptions about the characteristics of the photovoltaic cell being used.

Comparing Sources Directly

The simplest way to compare two light sources is to measure their intensities with the light meter at the same distance from each source. If one gives twice the reading of the other, then it is presumably twice as intense.

This presumption requires a number of things to be true. One is that the light meter is linear. That is, its output is directly proportional to the amount of light falling on it. You will evaluate its linearity in the next experiment, but here you may assume that it is linear.

Another assumption is that the meter is equally sensitive to the slightly different colors of candlelight and incandescent light. This so-called spectral sensitivity will be discussed in Section B, but again assume that each photovoltaic cell is equally sensitive to both.

3. *Adjust the distance* from the standard 40-W source to the detector until the meter reads a full deflection of 100 μA. Be sure to check the alignment of the box as discussed in step 2. Record this distance on the data page.

4. *Replace the standard lamp with the standard candle.* Be sure it is at exactly the *same distance* from the detector as the lamp. Again check the alignment. Record the new meter reading.

5. *Calculate the ratio of the intensities* by dividing one meter reading by the other. How many times brighter is the bulb than the candle, according to your calculations? How does this compare with your estimate by eye? Record your results on the data page.

6. *Repeat your measurements* with the silicon photovoltaic cell. Do you get the same ratio of intensities? If not, which assumption above do you think was not valid?

Comparing Illuminances

As you move away from a source of light, it appears to get dimmer and dimmer. This decrease in apparent intensity with distance obeys a well-known law of physics. You can use this law to relate the amount of light falling on a photodetector to its distance from the source. Later in this section, you will learn about this relation, but for the moment, assume that illuminance and distance are related.

If you know the relation between illuminance and distance, you need not know anything about the linearity of the detector. You can determine the relative intensities of two different sources by measuring the distances at which they produce the *same meter reading.* However, you must still assume that the detector is equally responsive to the light from each source.

7. *Adjust the distance* of the standard lamp from the detector until the light meter reads exactly half scale. Be sure the detector is accurately aligned. Then measure and record the distance from the *center of the bulb to the photovoltaic surface.* For convenience you may want to mark the location of the photovoltaic surface on the outside of the box.

8. *Replace the standard lamp with the standard candle.*

9. *Adjust the distance* of the standard candle until the photovoltaic cell gives the *same meter reading.* Again check the alignment. Then measure and record the new distance.

10. *Repeat your measurements* with the other photovoltaic cell.

A simple check will tell you that the ratio of the intensities is not just the ratio of the distances. Later you will see how to evaluate these results; record them for reference.

The purpose of this experiment is to measure the *linearity* and the *sensitivity* of the photovoltaic detector. As in the last experiment, this measurement relies on the fact that the illuminance of an object at various distances from a source can be accurately calculated if the intensity of the source is known.

Here, you will measure the output current of the detector at various distances from the standard source. Then you will make a graph of current against the calculated amount of incident light at each distance. If this graph is a straight line, then the photovoltaic cell is "linear" with light level. This graph can also serve as a *calibration graph* for your photodetector. From the graph you can easily read the illuminance for any output voltage.

The sensitivity of your photovoltaic cell can also be established. *Sensitivity* is the amount of output current that the photovoltaic cell gives per unit of illuminance. This value can be easily determined from your calibration graph.

Setting Up the Experiment

1. *Set up the components* of Experiment A-3, as illustrated in Figure 23. The light source should be the *standard 40-W lamp*. Initially, use the *selenium* photovoltaic cell.

2. *Record the intensity of the light source* in the data page. The intensity of the standard lamp should be written on it, or on a specification sheet for it. Be sure to record its units.

Measuring Output versus Distance

3. *Adjust the distance* between the photovoltaic cell and the standard source until the meter indicates exactly 100 μA on the scale. Again be sure the photovoltaic cell is properly aligned and "sees" all of (and only) the standard source.

4. *Measure and record the distance* at which the meter registers 100 μA.

5. *Increase the distance* between the photovoltaic cell and the light source by 10 cm. Again measure the detected signal. Continue to make measurements at 10-cm intervals from the light until the meter no longer deflects.

6. *Optional:* Repeat steps 3-5 for the silicon photovoltaic cell.

Measuring Illuminance

Later in the module these data will be used to make a calibration graph for your photodetector. Thus you can now use your photovoltaic cell as a light meter by recording the current output. Later you can use the calibration graph to relate these data to the illuminance.

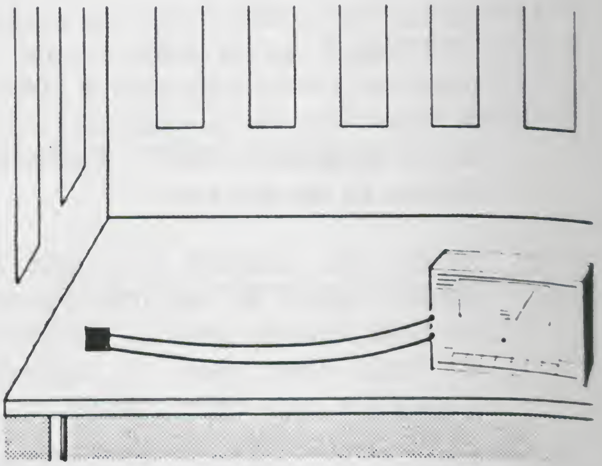


Figure 24. The light meter can be used to measure room illumination.

7. *Use your photovoltaic cell as a light meter* to measure the illuminance of various things. For example, how does the room illuminance vary in your laboratory? Remove the photovoltaic cell from the light-tight box, since here you want to measure the illuminance received from all directions. Record your results in the data page.

EXPERIMENT A-5 (OPTIONAL). Measuring Solar Power Output

One of the important uses of photovoltaic cells is to convert light energy into electrical energy. In this application the photovoltaic cell is often referred to as a solar cell, since it is generally the sun's (solar) energy that one wants to utilize.

In this experiment you will measure the electrical power produced for a given illuminance. You will learn that the amount of power produced depends greatly on what use is made of the electricity. In your experiment, you will vary the *load* on the photovoltaic cell by connecting resistors of various sizes across it. The goal is to determine the load resistance which maximizes the power output.

Procedure

1. *Set up the circuit* shown in Figure 25. The light source should be direct sunlight, if at all possible. If not, a 100-W lamp will serve. Initially, use the silicon photovoltaic cell. The voltmeter range should be about 0-1 V and it should be connected across the resistor. A selection of resistors (or preferably a resistance box) with values ranging between 10 Ω and 100 Ω should be available. (For an incandescent lamp source, you may need somewhat larger resistors.) Connect the smallest resistor across the photovoltaic cell.

   If you are using sunlight, point the photodetector directly at the sun. If you are using a lamp, be sure the detector sees only the lamp. Also, *record the distance* between the lamp and the detector.

2. *Measure the electrical power* generated for each of your load resistors. The photovoltaic cell generates an electrical voltage V across the resistor R. The electrical power produced in the resistor can be calculated from:

$$P = \frac{V^2}{R}$$

   where P is in watts if V is in volts and R is in ohms. Calculate the power as you go along so that you can determine the resistance which maximizes the power output.

3. *Measure the area of the photovoltaic cell.* Since the power produced by the photovoltaic cell depends on how large it is, you must know its area. Record your value *in square meters.*

4. *Repeat the measurement* with the selenium photovoltaic cell. Use the same source-to-detector distance.

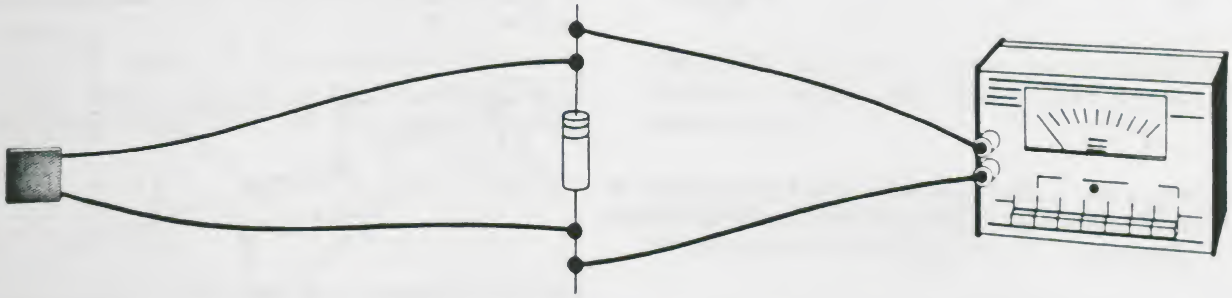


Figure 25. By connecting the photovoltaic cell across a resistive load, you can determine the amount of electrical power it produces. The light source can be either the sun or a lamp.

PHOTOMETRY

As we have indicated, the analysis of your data depends on the relation between intensity, illuminance, and distance. In the following, we discuss this fundamental relation of photometry.

"Point" Sources of Light

First, we will simplify the problem so that its solution is not too difficult. In this case the analysis will be limited to what are called *point sources* of light. A point source is one for which all the light comes from a very small "point" rather than from an extended surface.

There are no real point sources, but many sources act like a point source if they are far enough away. As a rule of thumb, a source may be considered a point source at *distances greater than ten times the source width.* For example, the light bulb used as a standard source was about 6 cm in diameter. Therefore, at distances greater than 60 cm, it acts like a point source.

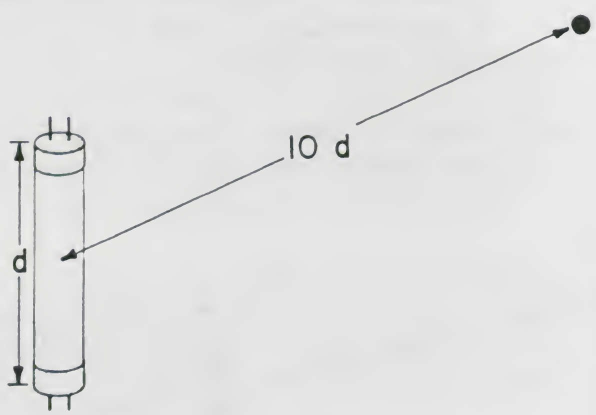


Figure 26. A light source acts like a point source at distances greater than about ten times its largest dimension.

Since light travels in straight lines, the flow of radiation in any direction looks like Figure 27. The light spreads out, illuminating a larger and larger area as it gets farther from the source. The total amount of light energy flowing within the spreading lines is constant, but the illuminance (light per unit area) decreases with distance.

Luminous Flux

Since the total amount of light within the spreading lines is constant, it is useful to give it a name, the *luminous flux F.* Flux is just another word for flow, so that the luminous flux is the amount of light flowing out from the source in a certain cone of directions, spreading itself thinner as it goes.

The flux in any cone is directly proportional to the luminous intensity I in those directions. (If the intensity varies within the cone, then the flux is proportional to the *average* intensity within the cone.) The direct proportionality can be expressed by:

$$I = kF$$

where k is a proportionality constant that depends on the size of the cone.

Flux and illuminance L are also related. Flux is the total amount of light crossing a given surface area A, while illuminance is the amount crossing a unit area. Therefore, the relation between them is:

$$L = \frac{F}{A}$$

This is consistent with Figure 27: a constant flux in any direction produces a decreasing amount of illuminance at increasing distances.

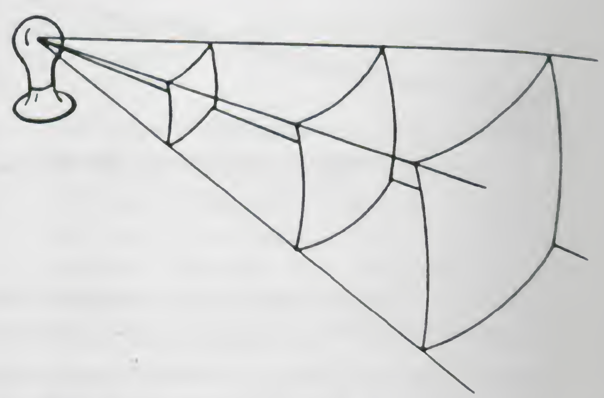


Figure 27. The luminous flux is constant but the illuminance on a surface decreases with distance.

The Inverse Square Law

The two equations involving flux can be combined to relate source intensity and object illuminance. This combination gives:

$$L = \frac{I}{kA}$$

Since we want to express L and I in terms of distance from the source rather than the area over which the light spreads, distance and area must be related. Figure 28 shows this relation. The curved surfaces of Figure 27 have been replaced by flat surfaces like that of your detector. This is a sufficiently accurate approximation for small areas (or large distances from the source).

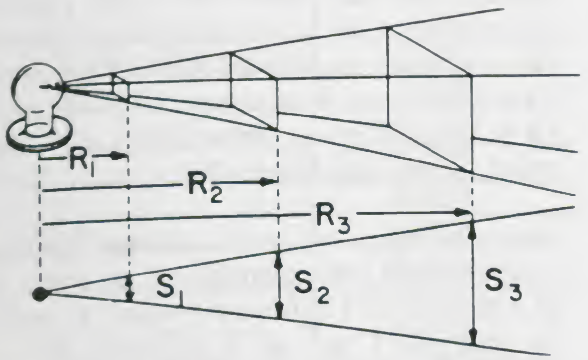


Figure 28. The area illuminated by a constant flux increases as R^2.

As indicated in the figure, the side S of the illuminated area is directly proportional to its distance from the source. This can be written $S = k'R$ where k' is a proportionality constant. Since the area A of the square is S^2, squaring both sides of the proportionality gives:

$$A = k'^2 R^2$$

Substituting this into the expression for illuminance gives:

$$L = K\frac{I}{R^2}$$

where we have combined the two constants of proportionality, k and k', into a single unknown constant K.

This expression is called the *Inverse Square Law* of radiation. It says that the illuminance of an object by a point source of light is directly proportional to the source intensity but inversely proportional to the *square* of its distance from the source.

The Generality of the Inverse Square Law

This law is quite general in physics. It always describes the decrease in energy received by an object at increasing distances from a radiating point source of energy. In photometry, the point source radiates energy in the form of light. If a point source such as a loudspeaker radiates sound, then the decrease in sound energy with distance follows the inverse square law. If the point source is a radio tower radiating radio waves, the decrease in electromagnetic energy with distance is also described by the inverse square law.

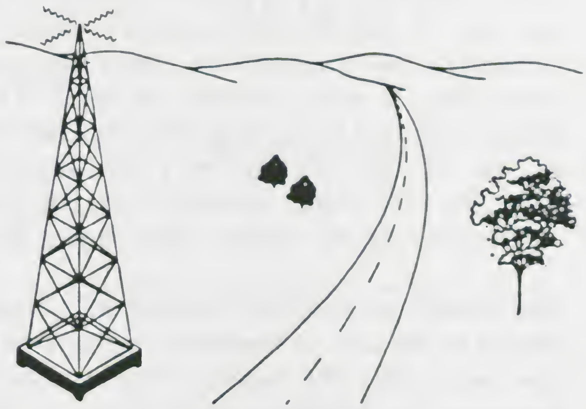


Figure 29. The inverse square law describes the decrease in energy with distance from any point source radiator.

For this law to be useful, however, we still need to know two things:

1. What is the value of the constant K?

2. What are the units of intensity I and illuminance L?

These questions are related. The *units* of intensity and illuminance *determine* the value of K.

PHOTOMETRIC UNITS

One of the problems of photometry is that what we call light depends primarily on what our eyes see. There are many different kinds of radiation, such as infrared, ultraviolet, radio waves, and so on, that are not visible to the human eye. You will learn more about this in Section B.

Luminous Intensity

In the process of inventing a photometer to compare the amount of light given off by lamps of various designs, Count Rumford chose as a standard a wax candle which uniformly consumed 108 grains Troy of wax every hour. Since this source emitted a constant amount of visible light and could be made in a reproducible way, it was eventually adopted as the *international standard candle.*

The luminous intensity of the standard candle was defined to be *one candle,* or *one candlepower.* However, as you have seen, candles are not easy to use in the laboratory. Modern technology has provided an easier way of reproducing a given amount of light. The present standard is based on the fact that the amount of light emitted by a hot, glowing (incandescent) object depends only on the temperature of the object. (See Figure 30.)

The change in standards resulted in a slight change in the unit of luminous intensity to a new unit called the *candela.* One candela is defined as the brightness of 0.016 cm^2 of the surface of a glowing object, such as a lamp filament, measured at the temperature at which platinum freezes (2045 K). One candela (cd) is equal to 1.02 candles.

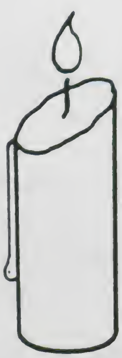


Figure 30. A candlepower (or candle) was originally the luminous intensity of a standard candle.

Luminous Flux

Defining a unit of luminous intensity allows us to define a unit of luminous flux. We know that the illuminance L is given by

$$L = \frac{F}{A}$$

$$= K \frac{I}{R^2}$$

where F is the luminous flux, A is the area of the object, K is a proportionality constant, I is the luminous intensity, and R is the source-to-object distance. We *arbitrarily* set K equal to one and define the *lumen* (unit of luminous flux F) as the amount of luminous flux crossing an area of one square meter ($A = 1\ m^2$) at a distance of one meter ($R = 1$ m) from a one-candela ($I = 1$ cd) point source. (See Figure 31.)

Since the same amount of luminous flux from a one-candela source crosses an area of 1 ft^2 at a distance of 1 ft from the source as crosses an area of 1 m^2 at a distance of 1 m from the source, the lumen (lm) also serves as the unit of luminous flux in the English system of units.

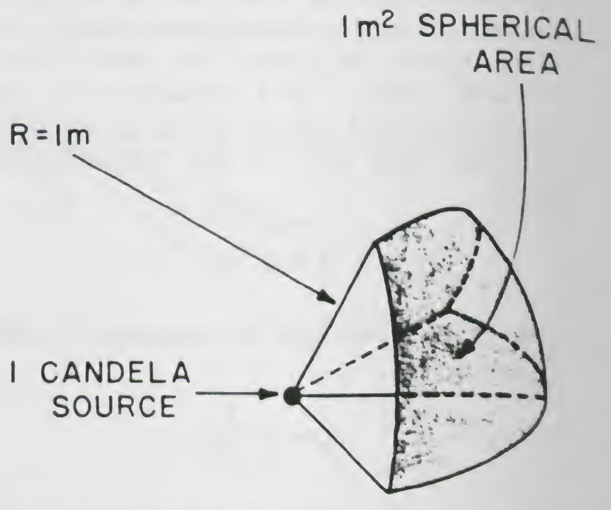


Figure 31. A lumen is the flux passing through an area of 1 m^2 at a distance of 1 m from a 1-cd source. At the spherical surface, the illuminance is 1 lm/m^2.

Since intensity is different in different directions, the important rating for light bulbs is the total amount of light that flows out in all directions. This is called the *total luminous flux* of the lamp. Table I shows typical total luminous flux values for ordinary incandescent lamps of various wattages. Also shown for comparison is the output of a 40-W fluorescent lamp. Note how much more luminous flux a fluorescent lamp puts out for the same electrical energy input.

Table I

Typical Luminous Flux Output of Incandescent Lamps

Power (W)	Luminous Flux (lm)
25	260
40 (Standard Lamp)	440
60	840
75	1,100
100	1,700
200	4,000
300	6,000
500	10,000
40 (Fluorescent)	2,600

Illuminance

The units of illuminance follow directly from the relation $L = F/A$. That is, if F is in lumens and A is in square meters, then illuminance is in *lumens per square meter*. One lumen per square meter is a *lux*.

$$1 \text{ lumen/meter}^2 = 1 \text{ lux } (1 \text{ lx})$$

The equivalent units in the English system are the *lumen/foot*^{2} and the obsolete *footcandle* (fc). A footcandle is the illuminance at a distance of 1 ft from a 1-candle source. If the detector were 1 ft from a 2-candle source, the illuminance would be 2 fc. (Note that this is not the same illuminance as at 2 ft from a 1-candle source.)

The SI and English units for illumination can be easily related, since they both involve 1 lm of luminous flux. Since 1 ft^2 is smaller than 1 m^2, 1 lm striking 1 ft^2 produces a greater illuminance than if it is spread over 1 m^2. (See Figure 31.) The relation between a meter and a foot is

$$1 \text{ m} = 3.280 \text{ ft}$$

Thus

$$1 \text{ m}^2 = 10.76 \text{ ft}^2$$

and

$$1 \text{ lm/ft}^2 = 10.76 \text{ lm/m}^2 = 10.76 \text{ lx}$$

Table II

Photometric Units

	Intensity I	Flux F	Illuminance L
SI Units	candela	lumen	$\dfrac{\text{lumen}}{\text{meter}^2} = \text{lux}$
English Units	candle	lumen	$\dfrac{\text{lumen}}{\text{foot}^2} = \text{footcandle}$

EVALUATING LIGHT DETECTORS

Knowing the inverse square law and the units for its terms, you can now analyze your experimental results. You must remember, however, that the law applies only to point sources of light. For the lamp this means measurements are made at distances greater than about 60 cm. At what distances does it apply to the candle?

Your Eye

The inverse square dependence of illuminance with distance is the basis for the equal-illuminance method of comparing two light sources. For each source:

$$L = \frac{I}{R^2}$$

If the distances from two sources, 1 and 2, are arranged so that they provide equal illuminance ($L_1 = L_2$), then:

$$\frac{I_1}{R_1^2} = \frac{I_2}{R_2^2}$$

or:

$$\frac{I_1}{I_2} = \frac{R_1^2}{R_2^2}$$

The ratio of the intensities equals the ratio of the *squares* of the distances that give equal illuminance.

1. *Calculate the ratio of the intensities* of the lamp (I_2) to the standard candle (I_1), using the distances that you measured when you estimated that the two sides of the viewing screen were equally illuminated. How does this compare to the direct estimate made by eye?

2. *Calculate the actual ratio of intensities* of the standard lamp and the standard candle. The standard candle is, by definition, a 1-cd source, so this ratio simply equals the rated intensity of the lamp in candelas. How does your estimate above compare to the actual ratio?

The Photovoltaic Cells

This method can also be applied to your light meter results. Remember, however, that you assumed that each of the photovoltaic cells was equally sensitive to the slightly different colors of candle and incandescent light. Thus you assumed that equal meter readings meant equal illuminance.

3. *Calculate the ratio of intensities* of the lamp and the candle, using your measured distances. Do this for both photovoltaic devices.

4. *Compare your results* with the actual ratio of intensities. The selenium results should agree fairly well, while the silicon results will not.

5. *Compare your direct meter reading results* with the actual ratio of intensities. Again your selenium photocell results probably agree, while the silicon results do not. However, the silicon results for the two methods probably agree with each other.

Conclusions

Your eye and the selenium photocell were both good judges of illumination. If you did your estimate by eye carefully, you may have been surprised at how accurately you estimated the ratio of intensities by the equal illuminance method. The eye, in fact, is quite a good judge of light, particularly in a comparative way. It was certainly much better than the silicon photocell.

The question now is what differences are there between silicon and selenium that make one accurate and the other not? The answer lies in their different sensitivities to color. This is discussed in Section B. Here we simply note that, because selenium is so closely matched to the eye, it is the photovoltaic cell most commonly used in light meters.

LINEARITY AND SENSITIVITY

The next step is to investigate the linearity and the sensitivity of the selenium photovoltaic cell. Again, you will rely on the inverse square law, but here you will use it to calculate actual illuminance. These results can then be used to draw a calibration graph for your light meter.

Calculating Illuminance

Since you recorded the intensity of the standard source, you can use it and the inverse square law to calculate the illuminance falling on your photovoltaic cell at the various distances measured in Experiment A-4. For example, if the luminous intensity of the bulb was 26 cd and the detector was 60 cm away, then the illuminance was:

$$L = \frac{I}{R^2} = \frac{26\ \text{lm}}{(0.6\ \text{m})^2}$$

$$= 72\ \frac{\text{lm}}{\text{m}^2}$$

1. *Calculate the illuminance of the detector* for each of the distances of Experiment A-4.

Drawing a Calibration Graph

These data can now be used to draw a *calibration graph* for your detector. This is a graph of the current output of your light meter against the illuminance falling on the detector. From this graph you can easily read off the illuminance for any meter reading you might have.

2. *Prepare a piece of graph paper* as shown in Figure 32. Put calculated illuminance on the vertical axis and photodetector current on the horizontal axis.

3. *Plot your data points.* For better visibility draw a geometrical shape, such as a circle, around each point.

Do your data points fall on a straight line? Probably the ones at farther distances do but the ones close to the bulb do not. Do you know why? Recall the requirements of a point source. You should find that the ones beyond about 60 cm do fall nearly on a straight line. Thus the current output of your selenium photovoltaic cell is *linear* with illuminance.

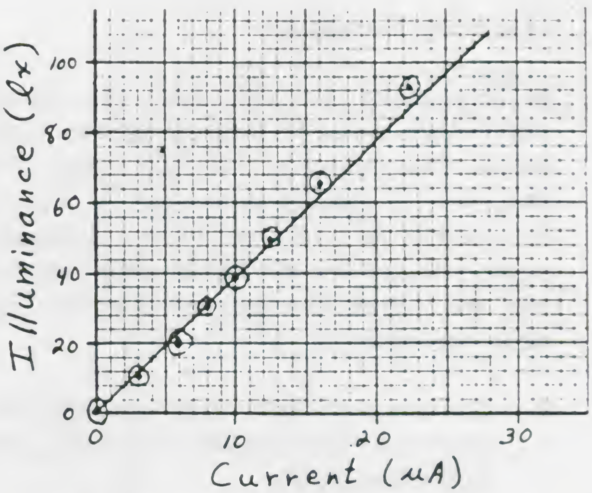


Figure 32. Portion of a typical photodetector calibration graph.

4. *Draw the best straight line* you can through the data points for which the inverse square law applies, ignoring the points taken too close to the source. The line should go through the origin. (Why?) This graph is your calibration graph.

Determining Sensitivity

You can also calculate the sensitivity of your photovoltaic cell from this graph. The sensitivity is the amount of current that the photovoltaic cell puts out per unit of illuminance. It is just the reciprocal of the slope of the straight line in the graph.

5. *Calculate the sensitivity of your photovoltaic cell* in μA per lx (lm/m^2). (For example, in the graph of Figure 32, since the illuminance is about 100 lx at 25 μA, the sensitivity is about 0.25 μA per lx.) Also, find the inverse of the sensitivity for later use. Which is more sensitive, silicon or selenium? How might you increase the sensitivity of the light meter?

Comparing Illuminance

In Experiment A-4 you used your photovoltaic light meter to measure various illuminances. The output of the light meter, however, was in current units, not in units of illuminance. Now that you have a calibration graph, you can convert these current readings into the actual illuminances that the light meter was receiving.

6. *Convert your light meter readings* from current to illuminance in lux, using your calibration graph.

Table III shows the minimum recommended illuminance for various situations, as taken from the U.S. Illuminating Engineering Society Lighting Handbook. These minimum standards serve as a guide for determining how much lighting is required for various situations.

7. *Compare your measured illuminances* with the values listed in Table III.

It should be noted that the values given in Table III represent from five to ten times the minimum values accepted as standard by the rest of the world. As energy becomes more and more expensive, these U.S. standards may well be revised downward.

For a further comparison, Table IV gives some typical values of illuminance by various natural light sources. Note how much brighter the sun's illumination is compared to artificial illumination. Yet our eyes are able to accommodate such extremes of illumination.

Table III

Recommended Values of Illuminance
Artificial Illumination

Area	Lux
Fine Inspection Work	22,000
Fine Bench Work	5,500
General Offices	1,100
Classrooms	770
General Home Lighting	550
Store Lobbies	330
Exterior Buildings and Yards	55
Auditoriums	1

Table IV

Approximate Values of Illuminance
Natural Illumination

Sky Condition	Lux
Direct Sunlight	120,000
Full Daylight (Not direct sunlight)	15,000
Overcast Day	1,000
Twilight	10
Full Moon	0.1
Night Sky (Clear, but moonless)	0.001

THE PHOTOVOLTAIC "SOLAR CELL"

The optional experiment, A-5, was devoted to measuring the electrical power output of a solar cell for a given illumination. If you have not done that experiment, take a moment to read it now so you will know what is involved. By reading the experiment you should be able to understand the following discussion, which explains the behavior of photovoltaic solar cells.

One thing we want to know is how much electrical energy a photovoltaic cell can generate for a given amount of solar illuminance. This is particularly important because solar cells may become a major source of energy. The sun radiates considerable energy toward the earth, and solar cells may provide one way of tapping that energy for home consumption.

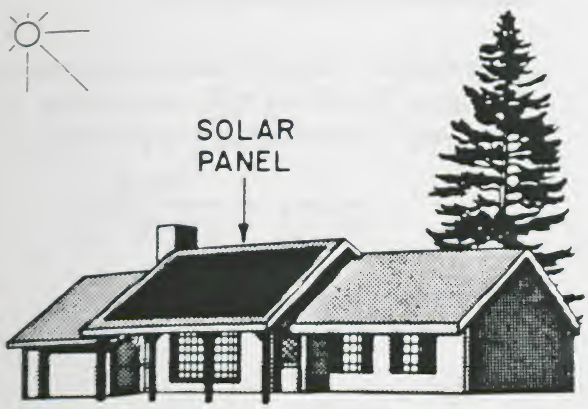


Figure 33. Solar cells may become widely used to provide energy for homes.

We also want to know which type of solar cell, silicon or selenium, is more efficient. You have seen that selenium makes a better light meter—but is it also better at converting light into electrical energy?

Maximizing Electrical Power

To determine which cell is a better converter of energy, you can compare the maximum amount of power each generated for a given illuminance.

1. *Construct a graph* of your calculated electrical power in milliwatts ($1\ mW = 10^{-3}\ W$) versus load resistance in ohms for both the silicon and selenium photocells.

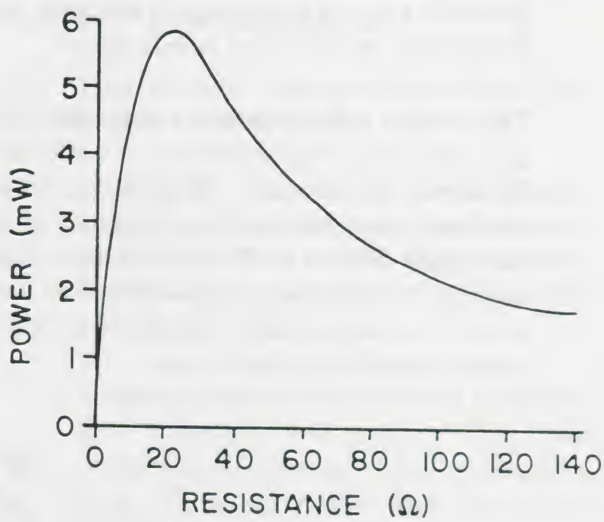


Figure 34. The power from a solar cell has a maximum for a specific load resistance. The value of the load resistance needed to produce maximum power depends on the illuminance.

2. *Draw a smooth curve* through the points. You should find that the power increases to a maximum and then decreases with increasing load resistance, as in Figure 34.

3. *Calculate the power developed per unit area* for each of your photovoltaic cells. Use the maximum power developed, as taken from your P vs R curves, and the measured area in square meters of each photovoltaic cell.

Comparing Photovoltaic Materials

If the sun was your light source, you should find that silicon produces nearly 20 times as much power from a given amount of light as does selenium. For this reason solar cells are made primarily of silicon. Silicon is convenient since it is the most abundant element on earth and it is therefore inexpensive. Selenium, on the other hand, is considerably less abundant and more expensive.

Radiated Power from the Sun

The sun, like most light sources, emits radiation other than visible light, such as ultraviolet and infrared radiation. While the eye does not respond to this radiation, the solar cells do. Therefore, when we discuss the power radiated from the sun, we must include radiated power of all types, and not just visible light.*

The average solar power per unit area striking the earth (the *solar constant*) is 1400 W/m^2. However, the amount of radiation actually reaching the earth's surface depends on how much gets filtered by the atmosphere. This, in turn, depends on where you are, what month it is, the time of day, the cloud and atmospheric conditions, and so on.

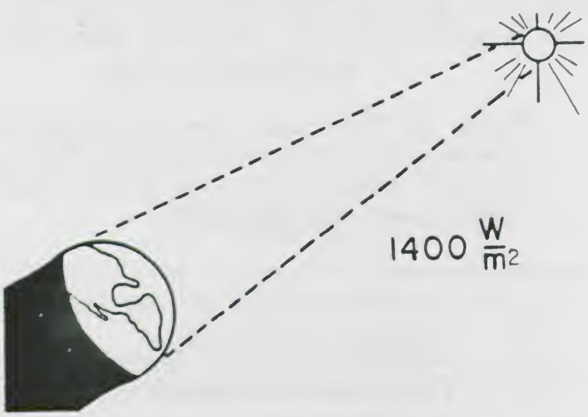


Figure 35. The earth receives about 1400 W/m^2 of radiated power from the sun.

For example, suppose you are in Terre Haute, Indiana in July. A typical *average daily* solar radiation on a clear day is 340 W/m^2. On an average cloudy day it is only about 270 W/m^2. In January, the corresponding values are 120 W/m^2 on a sunny day and 70 W/m^2 on a cloudy day.

*The science of total radiation measurement is called *radiometry*. Photometry is a sub-field of radiometry. Some of the principles of radiometry are treated in Section B.

Solar Cell Power Generation

Since it is difficult to determine the exact amount of solar power falling on your detector at the time you measured the electrical power, it is not possible to get a value for the conversion efficiency of your photovoltaic cell. The conversion efficiency is the percent of incident solar power that gets converted into useable electrical power. Typical values range from a few percent up to as much as 20 percent, depending on the quality and design of the cell.

You can, however, use your data to get some idea of how great an area of solar cell is required to produce a useable amount of electrical power. For example, how large must a solar cell be to light a 100-W lamp? Since the total power output is directly proportional to the area of the solar cell, you can calculate how large an area of solar cell is required to light a 100-W lamp under the solar conditions of Experiment A-5.

For example, using the maximum power given in Figure 34, $P = 6$ mW, for a solar cell of $A = 1$ cm^2 we can set up the proportion:

$$\frac{A}{10^{-4}\ \mathrm{m}^2} = \frac{100\ \mathrm{W}}{6 \times 10^{-3}\ \mathrm{W}}$$

Solving for the area needed:

$$A = 1.7\ \mathrm{m}^2$$

Thus, under the solar conditions for which the data of Figure 34 were taken, 1.7 m^2 of silicon solar cell is required to light a 100-W lamp.

4. *Calculate the area of solar cell* required to produce 800 W* of power, using your results of Experiment A-5.

*This is a typical average electrical power used by U.S. homes.

SUMMARY

In these experiments a photovoltaic light meter was calibrated with a standard source of light. To do this, the inverse square law of photometry, $L = I/R^2$, was used to relate the source intensity (I) to the illuminance (L) actually received by a detector at a distance (R) from the source.

Using the calibration graph, you were able to evaluate the *sensitivity* and *linearity* of the photovoltaic cell. The same procedures could be used to measure these properties for any photodetector.

The electrical power produced by a given amount of solar illuminance was also measured. This was found to have a maximum for some particular value of load resistance. When used in this way, photovoltaic cells are called "solar cells."

PROBLEMS

1. What is the intensity of a light which produces 100 lx at 10 m?

2. How much light falls on a 1-cm^2 detector 2 m from a 1000-cd light? Express your answer in lumens.

3. How far must you be from a 64-cd light source to receive 4 lx?

4. One meter from the overhead fluorescent tube, the illuminance is measured to be 3000 lx. Two meters from the tube, the illuminance is 1500 lx. How would you explain this?

5. A square photocell was found to deliver 0.33 V across a 1-Ω resistor. What is the conversion efficiency of the photocell if it is 10 cm on a side and was placed 30 cm from a 300-cd source?

SECTION B

Spectral Characteristics

INTRODUCTION

In Section A you observed that the selenium photocell judged the relative intensities of the candle and the standard bulb fairly accurately, as did your eye. The silicon photocell, on the other hand, saw the candle as brighter than it really was. This incorrect measurement was attributed to the difference in color of the two sources.

Spectral Sensitivity

The response of a particular detector to different colors is called its *spectral sensitivity.* This property is a measure of the relative sensitivity of the detector to the various colors of the spectrum (red, orange, yellow, green, blue, and violet). For example, does the detector give the same reading when illuminated by the same amount of light, regardless of whether the light is blue or yellow? (Figure 36.)

The same question can be asked about the eye. Does it see equal amounts of different colors as equally bright? There are obvious limits to what your eye can see. For example, it does not respond at all to ultraviolet and infrared radiation. But, in the visible region, does it see all the colors of the spectrum equally well?

Spectral Emission

Accurate measurements of spectral sensitivity, for either a photodetector or your eye, are difficult to make. The reason is that there are no light sources which put out equal amounts of all the colors of the spectrum.

Real sources (candles, incandescent lamps, fluorescent lamps, the sun, etc.) may all emit light that looks very nearly white. But each is actually made up of quite different amounts of various spectral colors. The relative amounts of the various colors is called the *spectral distribution.*

To measure the spectral sensitivity of your photodetector, you will perform an experiment that is quite similar to that shown in Figure 36. However, the resulting measurements will be a combination of the spectral sensitivity of the detector and the spectral distribution of the source. Fortunately, the spectral distribution of an incandescent lamp is well known. Thus you can use that information to separate out the two effects.

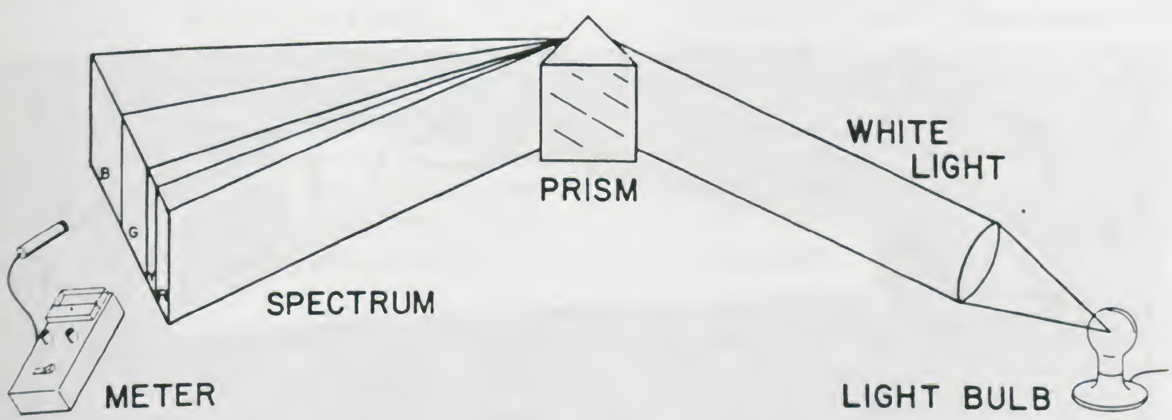


Figure 36. This section will investigate the way a photodetector responds to different colors of light (spectral sensitivity). Accurate measurements are difficult since no sources have a uniform spectral distribution.

As in Section A, you will begin by evaluating the performance of your eye. To obtain light of various spectral colors, you will need a high-intensity white-light source and a means of "dispersing" it into its component colors. Use an incandescent lamp, such as that of a slide projector, for a source. Use a diffraction grating to break up the light into its spectral colors. A grating is better than a prism since it disperses the colors more uniformly than a prism.

Figure 37 shows one possible arrangement, using a slide projector and a transmission diffraction grating. To reduce the overlapping of the colors in the spectrum, you must place a narrow slit in the slide holder of the projector. Figure 38 shows how to make a slit from a cardboard frame taken from an old slide and two razor blades.

You will also need a screen with a scale for measuring the color locations. Figure 37 also shows a simple screen made from white paper taped to the lower part of a meter stick. The spectrum shows brightly on the paper and the relative position of the colors can be read from the meter stick.

Obtaining a Spectrum

1. *Set up the arrangement* shown in Figure 37, or some equivalent arrangement, to produce a spectrum. You should find that the grating produces a central white light with several spectra on either side.

2. *Adjust the system* until the width of the first spectrum to the right of the central white light is exactly 30 cm. The width depends on how far the screen is from the grating, so you will have to adjust this distance. For later convenience arrange the screen so the spectrum extends from 40 cm (violet) to 70 cm (red) on the meter stick.

3. *Focus the projector* so that the central white light becomes a focused image of the narrow slit. Focusing the white slit gives the least possible mixing of colors in the spectrum. You now may have to readjust the screen distance.

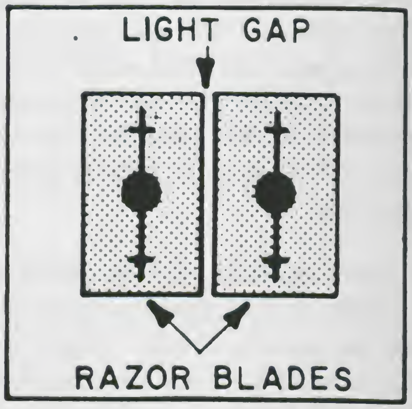


Figure 38. How to make a variable-width slit for the projector.

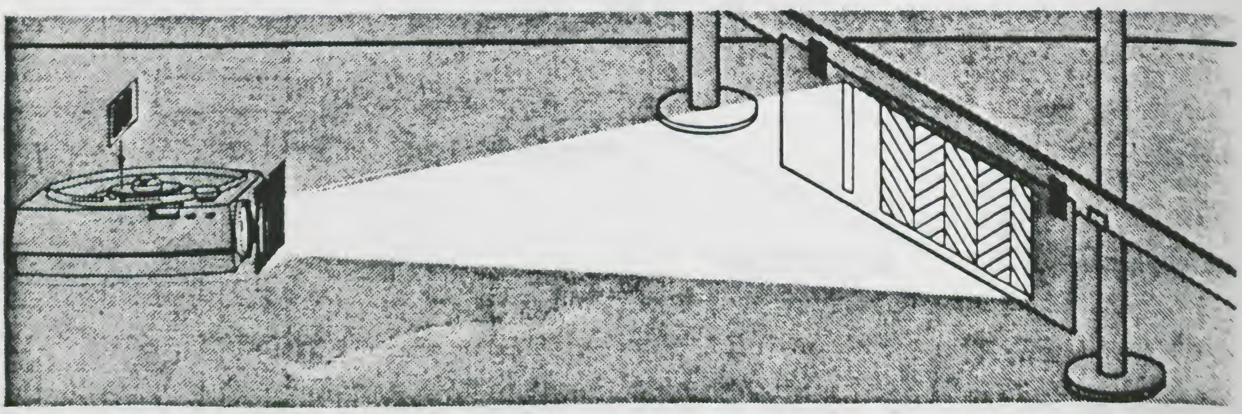


Figure 37. A way of producing a spectrum using a slide projector and a diffraction grating. The central white light should be a focused image of the slit in the slide, and the spectrum should extend from 40 cm to70 cm on the meter stick.

Viewing the Spectrum

Look carefully at the spectrum. You should find that the six basic spectral colors (red, orange, yellow, green, blue, and violet) blend smoothly from one to the next, but each can be readily identified. The color bands are also of unequal width; for example, the red band is broader than the yellow band. To make these observations more quantitative, try to estimate the exact range of the spectral colors along the meter stick.

4. *Make a graph* with the horizontal axis giving the spectral position on the meter stick in *millimeters* and the vertical axis going from 0 to 1. (See Figure 39.)

5. *Record the positions of the boundaries* of the six basic colors along the bottom of your graph. This can only be a best estimate, but do the best you can.

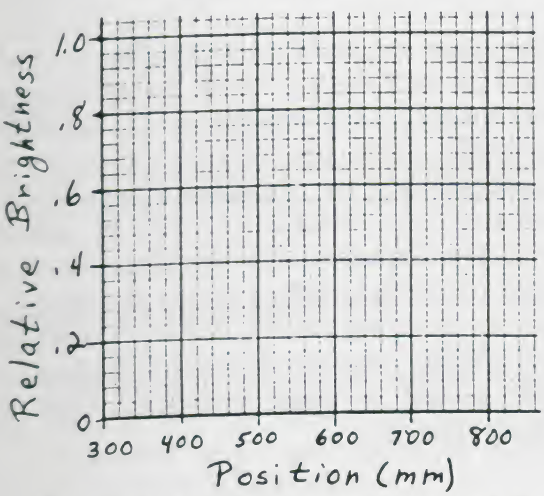


Figure 39. Graph for recording the spectrum.

Estimating the Spectral Brightness

The relative brightness of the colors is more difficult to judge. It is somewhat easier if you let the colors shine directly into your eye.

CAUTION: *The projector light is very intense and can damage your eyes. Be careful!*

The spectrum can be viewed directly from behind the meter stick as shown in Figure 40. It is essential to adjust the intensity of the light so it is bright enough for viewing but *is not painful!* To make the color locations more exact, view the spectrum through a small hole punched in a card.

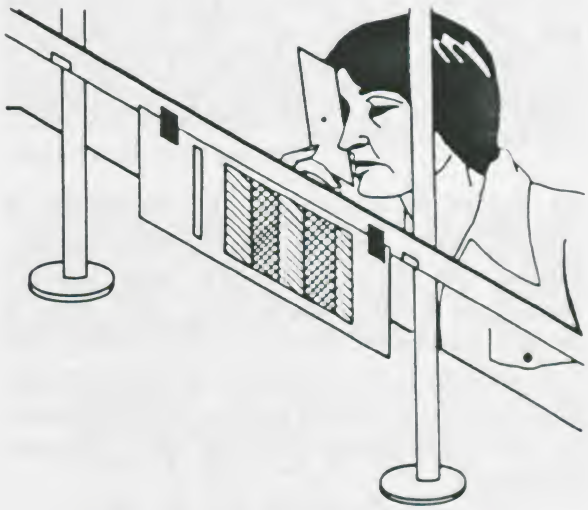


Figure 40. How to view the spectrum.

6. *Adjust the intensity of the spectrum* so it is bright, but comfortable to view through a small hole in a card. This can be done by changing the width of the gap in the projector slide or the size of the hole in the card, or both.

7. *Estimate the relative brightness* of the various parts of the spectrum on a scale from 0 to 1. Move your head back and forth along the spectrum to determine the positions where *no color* is seen. In this way, locate the outer edges of the violet and red bands. These should be at about 400 mm and 700 mm. Record these meter stick positions on your graph as zero brightness. Then find the position (color) where the spectrum appears brightest. Assign the value one to this brightness and record its position on the graph.

   Fill in the rest of the graph by estimating the brightness at intermediate positions relative to the brightness of 1. Each is a best estimate, but do the best you can.

8. *Sketch a smooth graph* through your data points.

ABOUT THE PHOTOTUBE

In this section you will use a different kind of photodetector called a *phototube.* The phototube is an older type of photodetector that has been largely replaced by the newer devices like the photovoltaic cell. For our purposes, however, the phototube has a number of advantages. First, its working parts are visible and easy to understand.

As Figure 41 illustrates, the phototube is nothing more than a curved metal surface (called the *cathode*) and a wire (*anode*) housed in a clear glass tube. The tube is usually evacuated (vacuum phototube), but may contain a small amount of some gas (gas phototube) to achieve certain characteristics. In your experiments you will use a vacuum phototube.

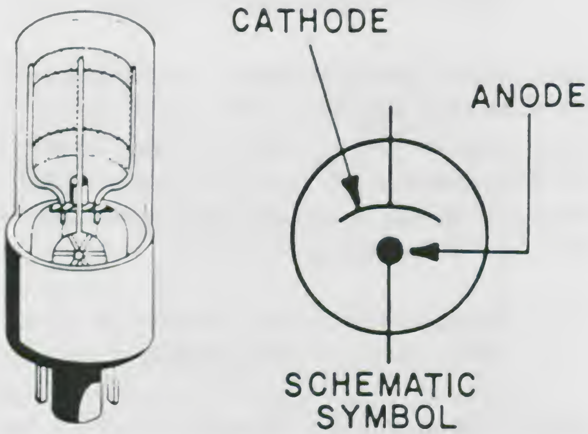


Figure 41. A typical phototube. It consists of a curved metal cathode and a wire anode in an evacuated glass tube.

The schematic symbol for the phototube is essentially a drawing of the phototube from above. It shows the curved metal cathode and the wire anode in cross section. Each of these is connected to the circuit, but there is no internal connection between them.

The Pin Connections

The base of the phototube contains several metal pins that fit a standard vacuum-tube socket. The cathode is connected to one pin

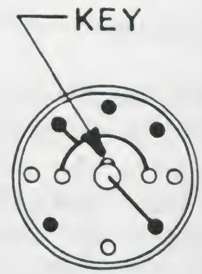


Figure 42. Bottom view of the phototube, showing the pin connections.

and the anode to another. The remaining pins are provided only for support in the socket. The connective pins can be identified relative to the keyway on the central plastic cylinder (see Figure 42). The key fits a corresponding slot in the socket to make sure that the tube is inserted properly.

The Photoelectric Effect

When light shines on the phototube, a current flows in an external circuit despite the fact that the anode and cathode are not connected internally. This phenomenon is called the *photoelectric effect.* In your experiments you will study this effect and see how the amount of current depends on the illuminance and the color of the light falling on the phototube, as well as on other factors. Later, in analyzing your results, you will find that this phenomenon reveals a basic paradox about the behavior of light.

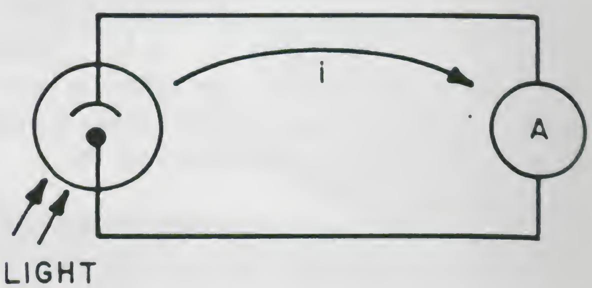


Figure 43. When light falls on the phototube, a current *i* flows.

The purpose of this experiment is to give you a general understanding of the phototube and what happens when light strikes it. To verify that a current flows when light strikes the tube, you can simply connect the phototube to a 0- to 100-μA ammeter, as shown in Figure 44. You will recall that this is exactly what you did with the photovoltaic cell.

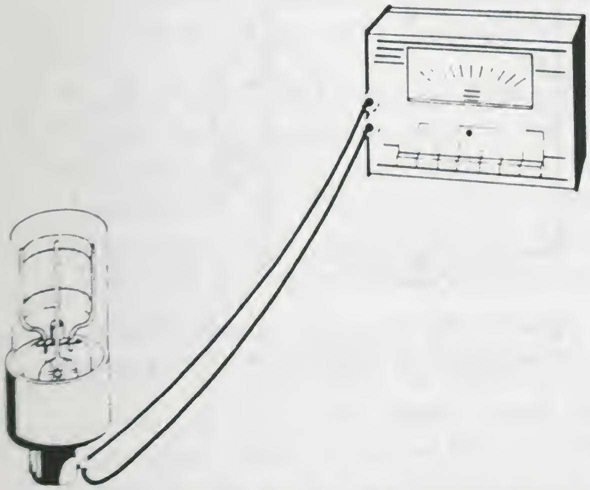


Figure 44. Connect the phototube to a microammeter and try to determine what causes a current to flow.

Observing the Photocurrent

1. *Examine your phototube.* Verify as best you can that the cathode and anode are connected to the pins shown in Figure 42, but not to each other.

2. *Connect the phototube to the 0- to 100-μA ammeter.* A tube socket with wires attached will make this much easier, but be sure to insert the tube so that its key fits the socket keyway.

3. *Expose the tube to light,* such as the room illumination, and observe how much current there is. You should detect some current, but the amount is quite small. How does it compare with the amount of current that a photovoltaic cell would produce for similar illumination?

Determining the Photosensitive Surface

How can there be a current in the circuit when the anode and cathode are not connected internally and the tube is completely evacuated? Take a moment to see if you can figure out how light falling on the tube might cause an electric current.

To explore this further, see if you can determine where the light must fall to cause the current to flow. For example, must it strike the anode or the cathode, or both?

4. *Investigate the light sensitivity of the phototube surfaces* by shining a narrow band of light on it. Use the focused image of the projector slit. Scan this bright band of light over the various surfaces to determine where the light must strike to cause a current.

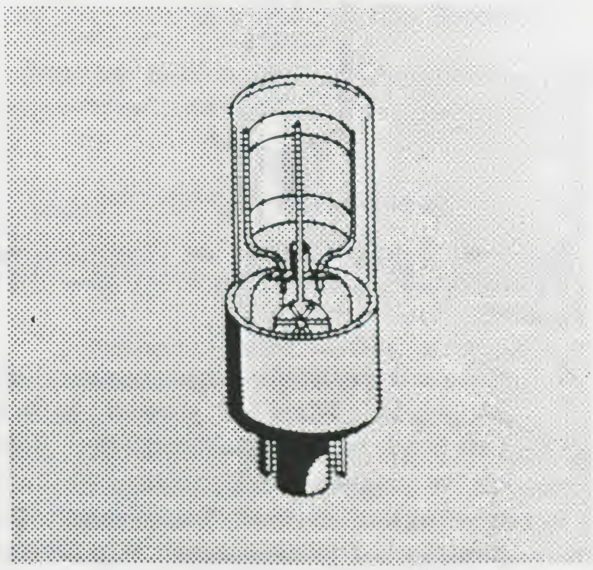


Figure 45. Scan a narrow band of light across the tube to determine its photosensitive parts.

You should find that the light must strike the cathode to cause current flow. In some way, light striking the cathode creates a current between it and the anode. When the light is removed, no current flows.

Establishing Particle Flow

What flows between the anode and cathode? To get a clue, recall that electrical current is a flow of electrically charged particles. Light *striking the cathode* must somehow release from the cathode *charged particles,* which then flow to the anode, producing a current.

There is a simple way to test this theory. When a charged particle moves through a magnetic field, it experiences a force. Therefore, if you put a magnet over the tube, as shown in Figure 46, you should be able to deflect the charged particles away from the anode, thus decreasing the current.

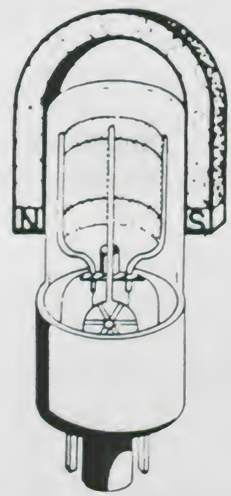


Figure 46. If charged particles are flowing between the cathode and anode, you can deflect them with a magnet.

5. *Rotate a horseshoe magnet around the phototube.* When a charged particle enters the region between the two poles of the magnet, it experiences a force at right angles to both the field and the direction of particle travel. You can use this fact to change the current by deflecting the particles emitted by the cathode away from the anode.

Determining Particle Charge

What is the charge on these particles? One way to determine the sign of the charge is to place a potential difference (voltage) between the anode and cathode and see how it affects the current. (See Figure 47.) A positive anode attracts negative particles and repels positive ones. A negative anode does the opposite. By noting whether the current increases or decreases with various anode polarities, you can determine the particle charge.

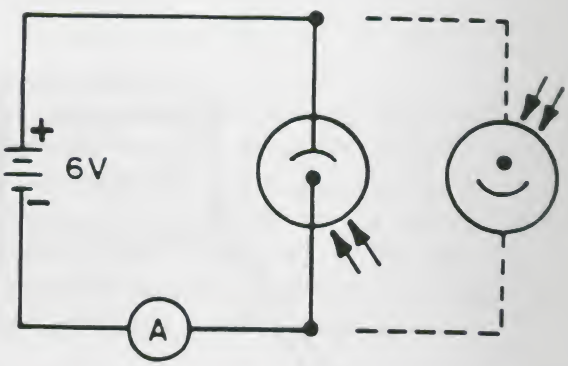


Figure 47. By changing the polarity of the anode you can determine the charge on the flowing particles.

6. *Set up the circuit* shown in Figure 47, using a 6-V battery and the 0- to 100-μA ammeter.

7. *Change the polarity of the anode,* as indicated by the dashed lines in Figure 47, to determine whether the anode must be positive or negative to stop the current. What is the charge of the current-carrying particles?

   Does the battery increase the current for a given illuminance? By how much?

A graph of the current i present in the circuit for various voltages V at a constant illuminance is called the *i-V characteristic* of the phototube. The i-V characteristics for various illuminances constitute an important technical specification for phototubes. A discussion of how the i-V characteristics of a phototube can be measured is given in the Optional Experiment, B-4.

In this experiment you will measure the spectral sensitivity of the phototube. The procedure is essentially the same as that used for the eye in Experiment B-1. The difference is that you can get quantitative data for the phototube, while only estimates were possible for the eye.

Setting Up the Experiment

1. *Set up the projector and grating* to produce a spectrum extending from 40 cm to 70 cm, as in Experiment B-1.

2. *Adjust the width of the gap* in the slide until the focused white image of the slit on the screen is *slightly smaller* than the cathode of the phototube. This ensures that, even for the narrowest color band, you will be able to fill the cathode with a single color.

3. *Mount the phototube in front of the screen* so it can be moved across the spectrum. Figure 48 shows one method, using a ring stand. To prevent stray light from reaching the phototube, it may be necessary to mount it in a light-tight box, as in Section A.

4. *Set up the circuit* of Figure 47 using a 6-V battery. The current produced by each spectral color will be small, since the phototube is not very sensitive.

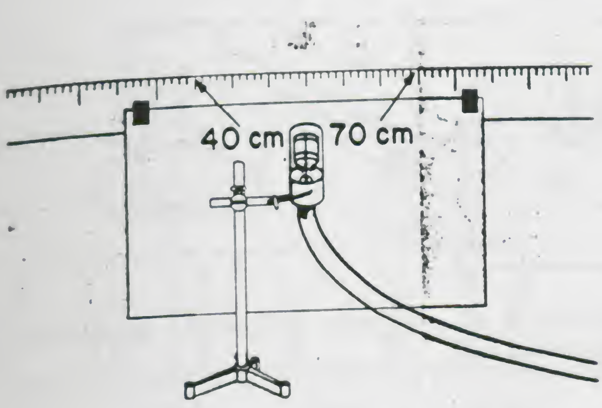


Figure 48. Mount the phototube so you can scan it across the spectral colors.

Amplifying the Phototube Output

To increase the signal, you can use an electronic amplifier.

5. *Connect an amplifier to the phototube* as indicated in Figure 49. Connect the cathode to the amplifier input and a meter (2 V full scale) to the output.

6. *Zero the system* by covering the phototube and adjusting the DC offset knob until the meter reads 0.

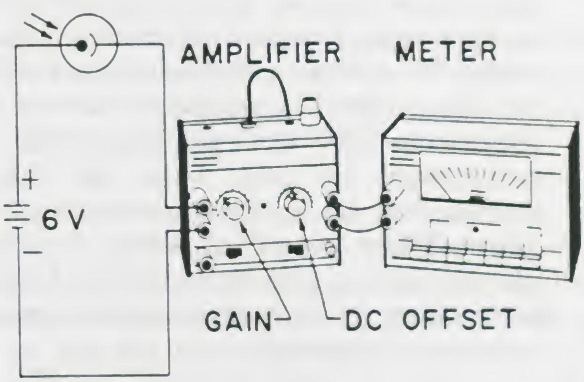


Figure 49. An amplifier increases the output so it can be more easily measured.

Measuring the Spectral Sensitivity

7. *Move the phototube across the spectrum* until you find the position giving the maximum meter reading (maximum current).

8. *Adjust the gain of the amplifier* at this position until the meter reads exactly full scale. *Recheck the DC offset* as in step 6. *Record the output and the position* in the table provided on the data page.

9. *Measure the phototube output* at 2-cm intervals on both sides of this central maximum. Extend the readings as far in either direction as the meter registers a readable output. This should be beyond the visible region of the spectrum.

EXPERIMENT B-4 (OPTIONAL). *i-V* Characteristics of a Phototube

You have seen that light shining on the photocathode liberates negatively charged particles which then flow to the anode to produce a "photocurrent." These particles are *electrons.* With no voltage applied to the tube, only those electrons which strike the anode by accident contribute to the photocurrent. If the anode voltage is positive with respect to the cathode, some of the electrons which would otherwise miss the anode will be attracted to it, thereby increasing the photocurrent (Figure 50).

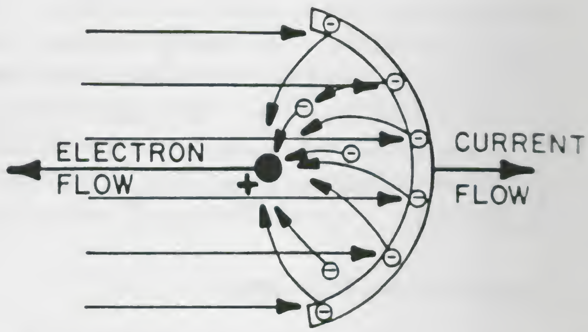


Figure 50. The photocurrent can be increased by attracting the negatively charged electrons to the positive anode.

In this experiment you will measure the current for various positive and negative anode voltages. Graphs of photocurrent versus voltage for different illuminances are called the *i-V* characteristic of the phototube. For comparison with the published technical specifications for your tube, you should measure the actual illuminance, using the calibrated light meter from Section A. As you take the data, try to interpret the changing photocurrent in terms of the electron behavior shown in Figure 50.

Procedure

1. *Set up the circuit shown in Figure 51,* using a 6-V battery, a 10-kΩ variable resistor, and a 100-μA meter. As a light source use a 100-W lamp or the projector.
2. *Adjust the distance* from the light source to the tube until the meter reads nearly full scale for 6 V on the anode.
3. *Measure the illuminance* of the phototube at this distance.
4. *Measure the photocurrent* at 0.5-V intervals, from about 6 V to 2 V.
5. *Repeat the measurements for several illuminances.*
6. *Graph your data* and compare it to the published data for your phototube.

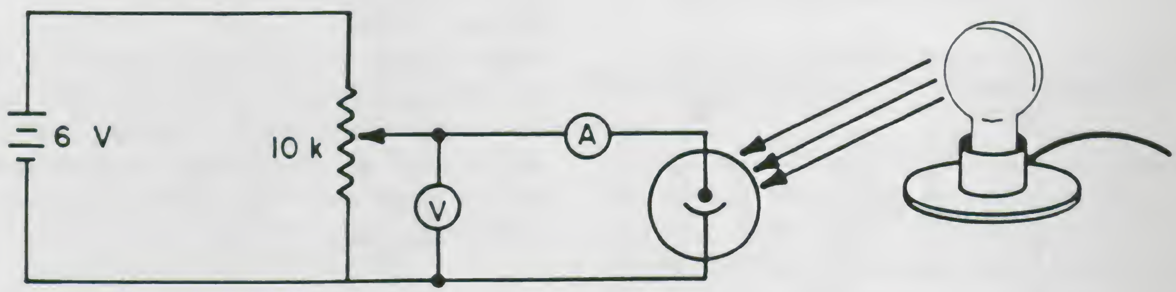


Figure 51. Circuit for measuring the *i-V* characteristics of the phototube. Measure the actual phototube illuminance so you can compare your results with the published data.

UNITS FOR THE SPECTRAL COLORS

The goal of Experiment B-3 is to determine the spectral sensitivity of the phototube. To do this you must be able to specify the various parts of the spectrum that the phototube measures. The color alone is not a precise measure since it is difficult to determine where one color ends and the next begins. Further, the phototube responds to light which is not visible to your eyes. Therefore, a more accurate method of specifying colors is required.

The Electromagnetic Spectrum

The visible spectrum is only a very small part of a much broader spectrum called the *electromagnetic spectrum.* This spectrum extends far beyond both ends of the visible spectrum and includes ultraviolet, infrared, x-rays, radio waves, and so on.

Figure 52 shows a schematic diagram of the electromagnetic spectrum, indicating some of the various types of radiation that it includes. The visible region has been magnified so that the ranges of the six basic colors can be seen. The radiation immediately beyond the violet end of the spectrum is called ultraviolet. "Ultra" is the Latin word for "beyond." Similarly, "infra" is the Latin word for "below," so that infrared is just below (or beyond) red in the spectrum.

Of particular importance are the numbers which designate the various parts of the spectrum. These numbers are called the *wavelengths* of the different radiations, and they are measured in *nanometers* (1 nm = 10^{-9} m). For the moment, simply regard these wavelengths as numbers which specify the various spectral radiations.

Comparing Your Spectrum

The visible region in Figure 52 ranges from about 400 nm to about 700 nm. These numbers represent only average values for the human eye, since the visual capabilities of people vary. The ranges for the various colors also vary from person to person. The numbers given are an accepted range, based on the average response of many individuals.

The choice of range for the spectrum in Experiment B-1, from 400 to 700 mm, allows you to compare directly your estimates of the ranges of the colors with Figure 50. A reading of 400 mm corresponds to a wavelength of 400 nm, and a reading of 550 mm corresponds to a wavelength of 550 nm, etc.

1. *Compare your graph of the spectrum* from Experiment B-1 with Figure 52. How well do your ranges for the various colors agree with the accepted values?

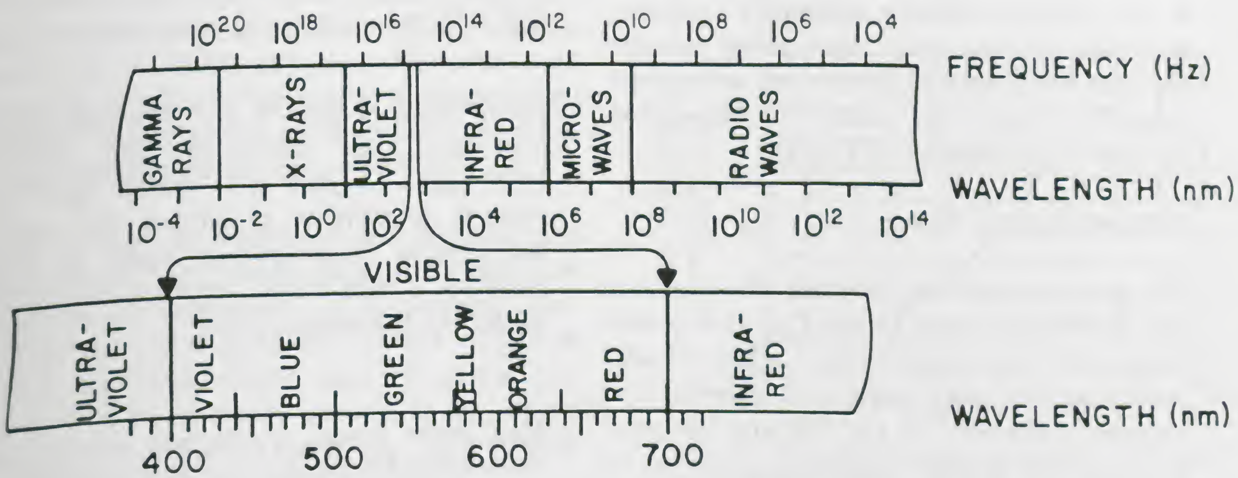


Figure 52. The electromagnetic spectrum, showing a magnification of the visible region.

SPECTRAL DISTRIBUTION OF SOURCES

In the introduction to the module, we noted that light sources do not necessarily emit the same amounts of the various colors. In order to determine the spectral sensitivity of the phototube, you must know the *spectral distribution* of the source you used. The spectral distribution of a source is ordinarily given as a graph of the *relative amount of radiation emitted at each wavelength.*

Measuring Radiation

To plot relative amounts of radiation, you must first know how amounts of electromagnetic radiation are measured. The science of measuring electromagnetic radiation is called *radiometry.* Photometry, which you studied in Section A, is a subfield of radiometry concerned only with measuring visible light. The photometric unit, the lumen, is defined for measuring visible light and is therefore not appropriate to nonvisible radiation.

In the solar cell experiment, however, you found that *energy* is associated with visible and nonvisible radiation. Since energy is one of the fundamental quantities of nature, and since it is easily converted from one form to another, energy is a logical quantity for measuring amounts of electromagnetic radiation.

If the radiation remains essentially constant, as it does in most cases, then *power* (energy per unit time) is a somewhat more convenient measure. Thus, the units for measuring "amounts of radiation" are *watts.*

Radiated Spectral Power

The *spectral power distribution* of a source is the number of watts radiated at each wavelength. By "each wavelength," what is really meant is over some *wavelength interval*; for example, between 500 and 501 nm. For your spectrum this means the amount of power in the light which illuminates the interval between 500 mm and 501 mm on the meter stick. The amount of light falling at *exactly* 500 mm is zero, since the *exact* position 500 mm is an infinitesimally small interval. One can choose any size interval, but the interval must be specified.

If the wavelength interval is 1 nm, then the spectral power will have units of W/nm. The spectral distribution is thus a graph of the amount of radiated power in 1-nm intervals centered at each wavelength.

The Sun

Figure 53 shows the spectral power distribution of sunlight. Note first that the vertical scale is in watts *per square meter* per nanometer. This is the amount of radiant power that falls on a square meter of the earth rather than the total amount actually emitted by the sun.*

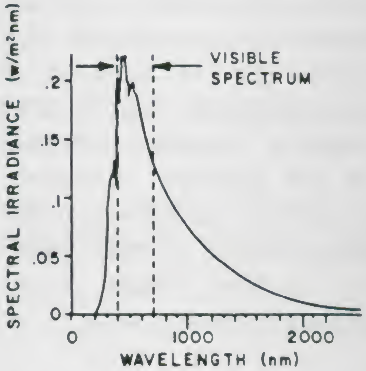


Figure 53. The spectral power distribution of the sun.

Recall from Section A that the *total power* per unit area falling on the earth is 1400 W/m^2. Figure 53 shows how that 1400 W is divided up among the various wavelengths. Note that the range of visible radiation is very nearly centered on the peak of the sun's radiated power.

*The power striking a given unit area in a unit wavelength interval is called the *spectral irradiance.*

Incandescent Lamps

The light source in your experiments was an incandescent lamp. An incandescent lamp is essentially a small coil of tungsten wire (the filament) encased in an evacuated glass bulb. The wire is heated electrically until it glows white hot. The spectral distribution of such a filament is shown in Figure 54. Notice that the peak of the curve is in the infrared region. Only a small fraction of the radiated power is in the visible. This explains why incandescent lamps are not terribly efficient light sources.

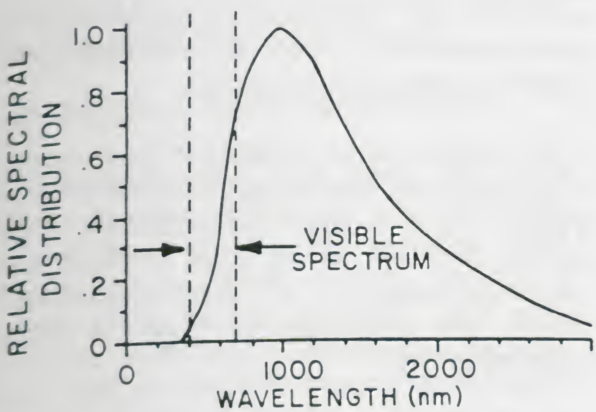


Figure 54. The relative spectral distribution of a tungsten filament at 2900 K.

The filament temperature is the key factor which determines a lamp's spectral distribution. The operating temperature in most common lamps is about 2900 K. If the filament temperature is increased, the peak of the curve shifts to the left, giving a higher fraction of visible radiation. However, tungsten filaments are less able to withstand these higher temperatures so that the lamp's lifetime will be shorter than at 2900 K.

Notice that in Figure 54 the vertical scale goes from 0 to 1, similar to your estimated intensity measurements of Experiment B-1. Thus the curve gives the *relative* output at each wavelength rather than the *actual* output. The relative output curve is of interest because it applies to any lamp, 5 W or 500 W, with a given filament temperature.

SPECTRAL SENSITIVITY OF DETECTORS

The spectral sensitivity of a photodetector also may be expressed as a *relative* curve, since the relative output does not depend on the illumination received. The actual output of a detector is then proportional to its relative sensitivity S times the relative distribution D of the source. This can be expressed:

$$\text{Detector output} = kSD$$

where k is a proportionality constant that gives the detector output in the proper units.

Experiments B-1 and B-3 yielded data on the output at various wavelengths, for your eye and for the phototube. If you know the spectral distribution D of the source, then dividing the output by D at each wavelength will give relative values for S.

Your Eye

This method can be used to determine approximately the spectral sensitivity of your eye. You can assume with sufficient accuracy that the horizontal axis of your estimated spectrum of Experiment B-1 is wavelength (in nm). For the source distribution D, use data appropriate to your particular source. If that is not available, use the data of Figure 55 for an incandescent lamp with a filament temperature of 3000 K.

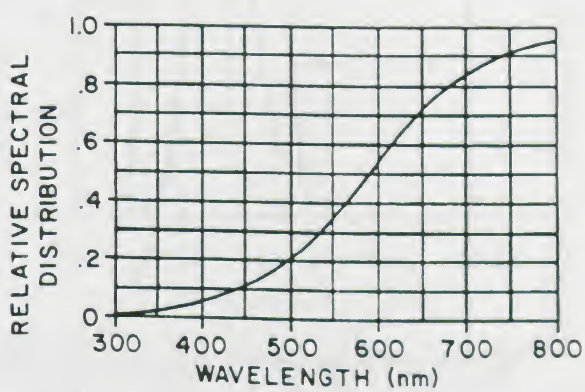


Figure 55. The spectral emission in the visible range of a tungsten filament at 3000 K.

1. *Divide each value on your graph* by the relative source distribution D at that wavelength. Take values of D from Figure 55 or from a graph appropriate to your source.

2. *Divide each of these values by the maximum value* in your new table. This will make the maximum value equal to 1.00, with the other data being some decimal fraction of 1.00. This process is called *normalizing* the data, and makes it easier to compare with other similar relative data.

3. *Make a graph,* similar to the original one, of the new data. Choose scales such that the curve is about twice as high as it is wide.

4. *Compare your graph* with the accepted spectral sensitivity of the human eye shown in Figure 56.

In spite of all the estimates and approximations that were made, you should find that your curve looks quite similar to Figure 56. Of particular importance is the wavelength of the peak. This is about 550 nm, which is in the yellow-green part of the spectrum. This means that your eye is much more sensitive to greens and yellows than to violets and reds. Incandescent lamps, however, put out substantially more red than violet light (Figure 55), so that the red in the spectrum still appears quite bright.

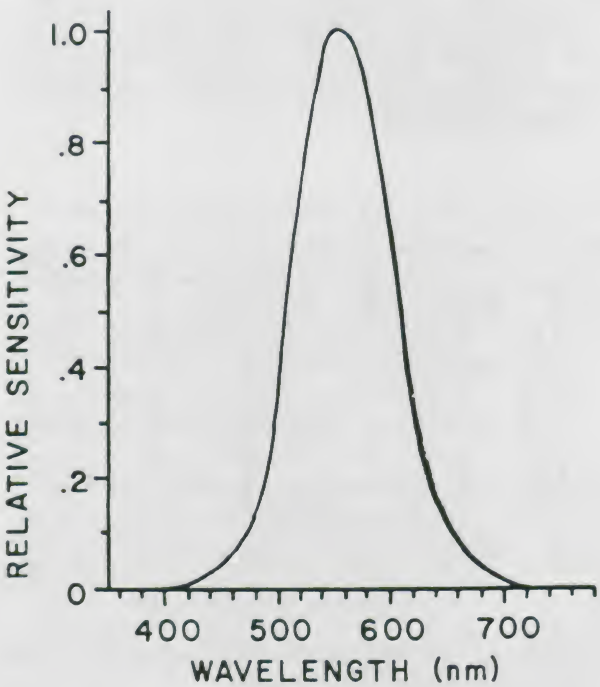


Figure 56. The spectral sensitivity of the human eye.

The Phototube

This same process can be applied to your phototube data of Experiment B-3. Again you can assume that the meter stick readings in mm are actual wavelengths in nm. If you set up your spectrum width carefully, this will not be far off. For accurate measurements of spectral sensitivity, of course, the wavelengths must be known more precisely.

If the actual spectral emission of your source is not available, you can again use the data of Figure 55 as a good approximation. You should find here, as for your eye, that the important features of the spectral sensitivity curves are reproduced in spite of these approximations.

5. *Divide each value of meter output* by the relative source distribution at that wavelength. Use the actual data for your source or the data of Figure 55.

6. *Normalize,* as in step 2.

7. *Make a graph of your data,* similar to that shown in Figure 56. This graph is now the measured spectral sensitivity of the phototube.

8. *Compare your curve* with the manufacturer's published data for this phototube, shown in Figure 57.

As was the case for your eye, you should find that your graph agrees quite well with the published data. In particular, note that the phototube's "long-wavelength cutoff" is nearly identical to the eye's (700 nm). The peak, however, is closer to the violet, so that it detects much more violet and ultraviolet than does the eye.

The Photovoltaic Cells

Also shown in Figure 57 are the spectral sensitivities of the selenium and silicon photovoltaic cells used in Section A. Notice how much more closely matched to the eye the selenium cell is than the silicon. The selenium responds more to violet and ultraviolet than does the eye.

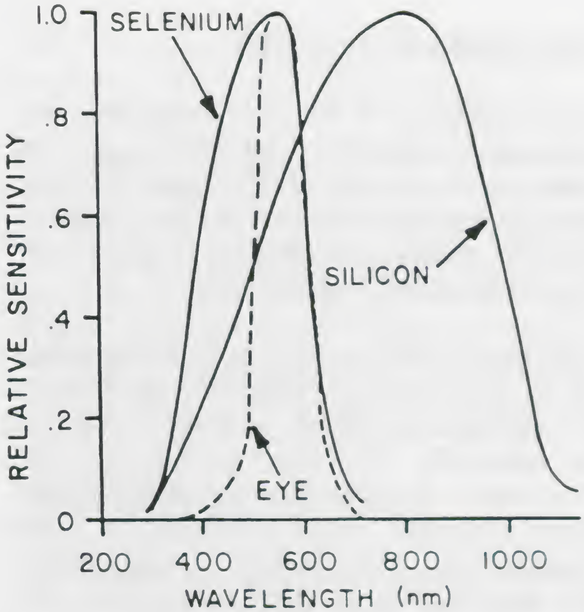
The spectral sensitivity of the silicon photovoltaic cell extends far out into the infrared, while the responses of the eye and selenium cells do not. Since incandescent lamps emit mostly infrared light (Figure 54), the silicon cell detects much more incandescent radiation than does either the eye or selenium.

Explaining the Short-Wavelength Cutoff

In Experiment B-2 you found that light falling on the cathode of the phototube released negatively charged particles which flowed to the anode, thereby creating a current. The spectral sensitivity data now show that only light of wavelengths between about 300 nm and 700 nm is able to release these charges.

The 300-nm cutoff, however, is not a characteristic of the photoelectric effect. Rather it is a characteristic of the *glass* in the phototube. Figure 57 also shows the *relative transmittance* of "lime glass," the special glass used for making phototubes. The relative transmittance is the fraction of incident light that gets through the glass.

Notice that the short-wavelength cutoff of the lime glass almost exactly matches the shape of the spectral sensitivity of the phototube on the short-wavelength end. If light of still shorter wavelengths could actually reach the cathode, it would also release charged particles. In fact, phototubes are sometimes made with special ultraviolet-transmitting materials, such as quartz, to extend their spectral sensitivity into the ultraviolet range.



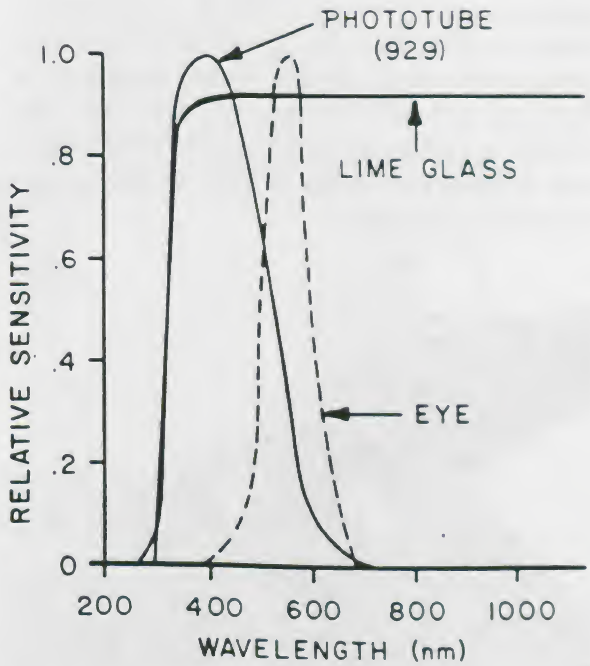


Figure 57. The spectral sensitivities of a number of detectors and the relative absorption of lime glass.

WAVE PICTURE OF LIGHT

The explanation of the long-wavelength cut-off is of considerably more interest. In providing an explanation of this feature, Einstein not only started a major revolution in physics, but also created a paradox about light which took many years to understand.

This explanation changed our understanding of the nature of light. Before the discovery of the photoelectric effect, light was thought to be essentially "wavelike" in character. By "wavelike" we mean that the radiation has some properties which are shared by more familiar kinds of waves, such as water waves. For example, waves carry energy from one place to another, and *periodic* waves oscillate in a repeating fashion.

For electromagnetic radiation, the quantities which oscillate are electric and magnetic fields. As these oscillating fields pass electrons or other charged particles, they produce forces which cause the charges to oscillate back and forth, and thus gain energy. This is analogous to the way in which a water wave affects a floating cork. As the wave passes the cork, it transmits energy to it, causing it to bob up and down. Yet, in order for this energy to be transmitted across a lake, it is not necessary to move a bulk of water from one side to the other.

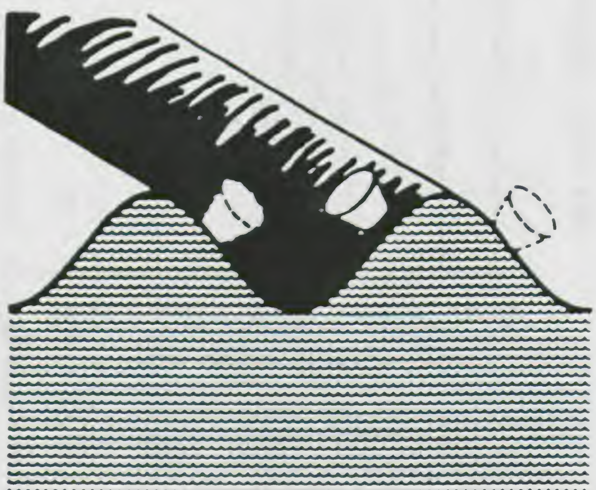


Figure 58. Electromagnetic waves affect charged particles in much the same way that water waves affect corks.

The Terms Which Describe Waves

A common representation of a wave is shown in Figure 59. For an electromagnetic wave, this graph might represent the variation in the size of the electric or magnetic field with distance. Equivalently, it might represent the size of the force experienced by a charged particle at any given position.

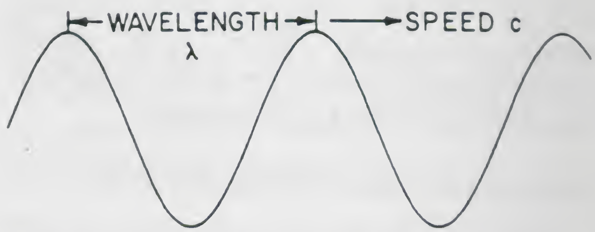


Figure 59. The standard representation of a wave.

The *wavelength* is the distance over which the basic wave shape repeats itself. For example, the distance between crests is one wavelength. It is this distance to which the wavelength specifications of Figure 52 refer. The "nano" in nanometers is a prefix meaning 10^{-9}; so waves of visible light are extremely short, 4×10^{-7} m to 7×10^{-7} m in length. Radio waves are relatively long, about 100 m. The wavelength of a given wave changes with the material the wave travels in. The wavelength values in Figure 52 are for a vacuum, but they are not significantly different for waves in air.

Electromagnetic waves all travel at the *speed of light c*, which is 3×10^8 m/s in a vacuum. When electromagnetic waves pass through materials, the wave speed decreases. In glass, for example, the speed of visible light is only about 2×10^8 m/s.

The number of complete waves passing a stationary point each second is called the *frequency f* of the wave. Frequency is the number of field (or force) oscillations that a stationary electron experiences each second. The unit, cycles per second (cps), is called a *hertz* (Hz).

A Wave Equation

The three terms which describe a wave (speed c, frequency f, and wavelength λ) are related by a *wave equation*:

$$c = f\lambda$$

This very general equation applies to all types of waves, including water waves and sound waves. It relates the speed of the wave to the frequency of its oscillations and the length between successive wave crests.

The value of c in a vacuum is the same for *all* electromagnetic waves. Thus, the wave equation can be used to calculate the frequency corresponding to each wavelength in the spectrum. For example, the peak of the human-eye sensitivity is $\lambda = 550$ nm. This corresponds to a frequency of:

$$\begin{aligned} f &= \frac{c}{\lambda} \\ &= \frac{3 \times 10^8 \text{ m/s}}{550 \times 10^{-9} \text{ m}} \\ &= 5.5 \times 10^{14} \text{ Hz} \end{aligned}$$

For a comparison of electromagnetic wave frequencies and wavelengths see Figure 52.

Frequency is perhaps the most fundamental property of an electromagnetic wave since the frequency does not depend on the material the wave travels in. The smaller speed resulting when a wave enters a material simply means a correspondingly shorter wavelength. The number of cycles that pass a given point per second, however, always remains unchanged.

Applications of the Wave Picture

The picture of light as an electromagnetic wave was able to explain most of the properties of light up to the discovery of the photoelectric effect. Using the wave theory of light, one could account for the reflection of light, the refraction of light, and all the various interference and diffraction phenomena (see Figure 60).

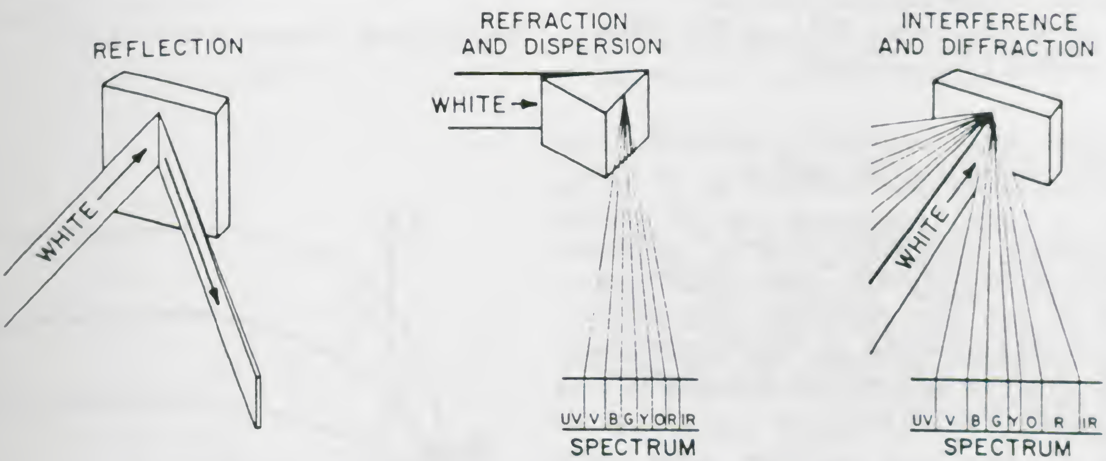


Figure 60. The wave picture of light can account for all of geometrical and physical optics.

THE PHOTOELECTRIC EFFECT

The phototube behavior investigated in Experiment B-2 is evidence of a light-matter interaction which the wave picture of light cannot explain. This phenomenon, in which light falling on a metal surface releases negatively charged particles, is called the *photoelectric effect.* The negatively charged particles are electrons.

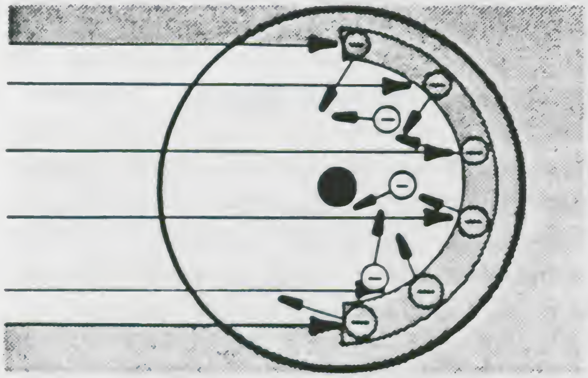


Figure 61. In the photoelectric effect, light falling on a metal surface releases electrons.

The Experimental Observations

To begin our discussion of the photoelectric effect, we will list the experimental observations that characterize it. One of these was hinted at in Experiment B-3, and the others can be verified by experiments.

1. *Above some particular wavelength of light, no electrons are emitted.*

"Above some wavelength" can also be stated as "below some frequency," since the two are related by the wave equation. This observation is valid *regardless of the illuminance*; even the brightest light will not eject electrons if the frequency is too low.

If you did the optional experiment to determine the *i-V* characteristics of a phototube, your results should be similar to Figure 62. This shows the dependence of photocurrent on cathode-anode voltage (both positive and negative) for various illuminances. These data, however, are for light of only a single wavelength.

When the anode is negative, a small current still flows! Some of the electrons in the cathode are able to overcome a negative voltage to reach the anode. This is observed only up to some voltage, called the *stopping voltage* V_0. The value of V_0 *does not depend on the amount of illuminance.*

The stopping voltage V_0 multiplied by the electron charge e is the energy of the most energetic electron emitted by the cathode for light of a particular frequency. The value of V_0 is directly proportional to the frequency.

This observation can be stated:

2. *The maximum energy of the emitted electrons is directly proportional to the frequency of the incident light.*

A final observation has to do with the *time response* of the phototube. This is a measure of how long after the light strikes the cathode a current starts to flow. The experimental observation is:

3. *There is no time lag between the time light strikes the cathode and the time of emission of the first electron, regardless of the illuminance.*

Time response is discussed in Section C.

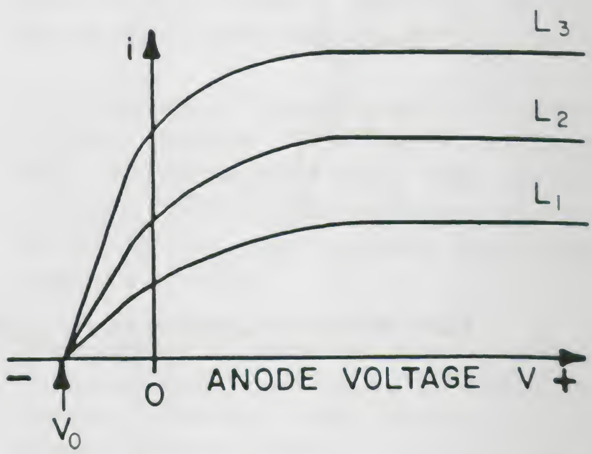


Figure 62. Typical *i-V* characteristics of a phototube for various light levels of illuminance of a single wavelength.

The Work-Function Energy

In analyzing the behavior of the phototube, one must account for the energies involved. Energy is required to extract an electron from the surface of the cathode. Electrons are held to the surface by an electromagnetic force of attraction. An electron must somehow obtain energy to escape this force.

This situation is analogous to the escape of objects, such as rockets, from the surface of the earth. A rocket is held to the earth by a gravitational force of attraction. In order to break free from this force, the rocket must obtain a certain minimum kinetic energy. Typically, this kinetic energy is expressed in terms of a minimum escape *velocity* (about 7 mi/s).

For an electron, this minimum escape energy is called the *work function,* since it takes this amount of "work" to pry the electron away from the atoms in the surface. The work function depends on the metal, and typical values range from about 2 to 5 *electron volts* (eV). An electron volt is a common unit for measuring electron energies. It is the amount of energy given to an electron when it is accelerated by a voltage of one volt. It is related to the joule by:

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

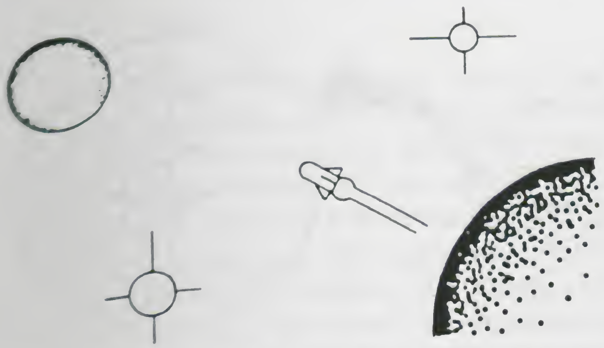


Figure 63. A rocket must have a certain kinetic energy to escape the earth's gravitational force. Similarly, an electron must get a certain energy to escape the electromagnetic force in a metal.

Applying the Wave Picture

In the photoelectric effect, the work-function energy must come from the energy of the incident light. An electron must "absorb" an amount of incident light energy equal to the work function in order to break free from the surface.

According to the wave picture of light, the energy in the light depends directly on the illuminance. Thus, for a phototube, one would expect that the number of electrons released per second (the photocurrent) would be directly proportional to the illuminance. This is indeed the case, as shown in Figure 64.

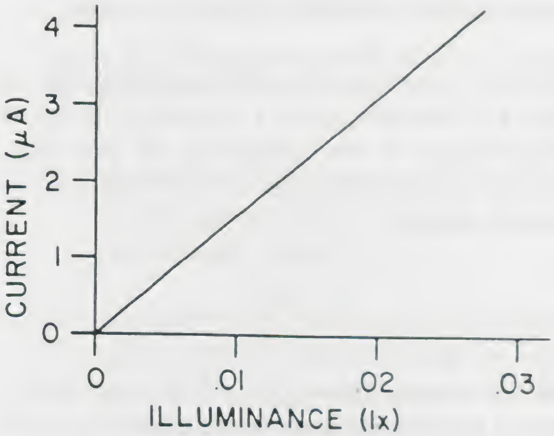


Figure 64. Only the dependence of photocurrent on illuminance agrees with the wave picture.

One would further expect that the energy gained by an individual electron would also depend on the illuminance. Thus, at any frequency, if the illuminance were large enough, some electrons would ultimately absorb energy equal to the work function and escape. Also, the maximum energy of the emitted electrons would depend strongly on the illuminance. Finally, at very low illuminance there should be some delay in the appearance of a photocurrent after the light is turned on, since it would take more time for electrons to absorb the energy necessary to escape.

None of these latter predictions of the wave picture are borne out by the experimental observations!

PARTICLE PICTURE OF LIGHT

The failure of the wave picture of light to account for the photoelectric effect puzzled some scientists. Earlier, Max Planck had been able to describe the radiation emitted by heated bodies, like the filament of your incandescent lamp, by assuming that the energy was emitted as a stream of tiny particles, rather than a uniform electromagnetic wave.

Photons

These light "particles" are now called *photons.* They have no mass or charge, like an electron, but are simply concentrated "bundles of energy". When light strikes a surface, these photons fall like a rain of massless, fiery hailstones on a cobblestone road, where the cobblestones represent the surface atoms.

Einstein extended the photon description of light by proposing that a photon's energy is proportional to the frequency of the light. That is, a photon in light whose frequency is f has an energy:

$$E = hf$$

The proportionality constant h is a fundamental natural constant, called *Planck's constant* in honor of Max Planck. It has the value:

$$h = 6.625 \times 10^{-34}\ \mathrm{J \cdot s}$$

Note that since frequency has units of hertz (1/seconds), E is in joules.

This relation says that the higher the frequency of the light (the shorter the wavelength), the greater the energy of its photons, and vice versa. Thus, violet photons are more energetic than red ones, ultraviolet more energetic than violet, and so on.

Photon-Electron Interaction

A metal, like the cathode of the phototube, is composed of many, many atoms held together by strong electric forces. The microscopic picture looks, to some extent, like a huge number of identical pebbles in a box. And the surface looks much like the cobblestone road mentioned earlier.

Between these densely packed atoms, electrons wander more or less freely. These are called ***conduction electrons*** since an applied voltage will cause them to move, all in the same direction, and thus constitute an electric current. It is these electrons which can be liberated by light, provided that they absorb the necessary energy.

According to Einstein's photon picture, photons strike these electrons. Each photon that is absorbed by an electron transfers *all* of its energy to the electron. Since a photon is only energy, it then disappears. This suggests that a photon in the incident light must have at least the work-function energy in order to liberate an electron. If the work function of the material is ϕ (Greek letter *phi*), this implies that:

$$hf_{\min} = \phi$$

where $f_{\min}$ is the minimum-frequency light able to produce the photoelectric effect in the material.

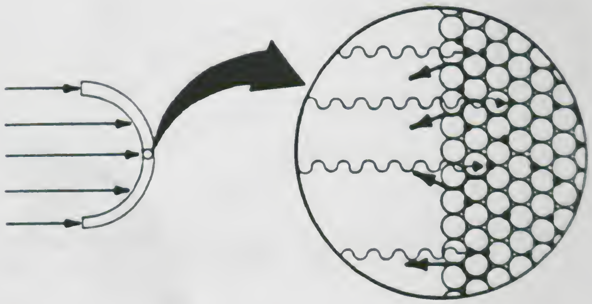


Figure 65. The particle picture of the photoelectric effect.

Explaining the Photoelectric Effect

This picture of the photon-electron interaction explains all of the experimental observations of the photoelectric effect. For example, f_{min} corresponds to the long-wavelength cutoff λ_c of the phototube. From the wave equation $\lambda_c = c/f_{min}$. Thus:

$$\lambda_c = \frac{hc}{\phi}$$

where λ_c is the longest-wavelength light that would produce a photoelectric effect in a material of work function ϕ.

This also explains the dependence of the maximum electron kinetic energy on frequency. For light of frequency greater than f_{min}, the electrons have "energy to spare" after being ejected from the surface. If the liberated electrons do not lose any additional energy in getting out of the surface (for example by collisions), they will have the maximum energy:

$$E_{max} = hf - \phi$$

This is the incident photon energy minus the work-function energy necessary to escape the surface.

And finally, there is no time lag for emission at any illuminance, since even the first photon that strikes the surface can liberate an electron if it has the minimum required frequency.

Determining the Photocathode Work Function

From this discussion, you can see that the long-wavelength cutoff of the phototube's spectral sensitivity curve is directly related to the work function of the cathode material. The only difficulty is in determining the *exact* cutoff wavelength. As a good approximation you can simply extend the steeply falling curve to where it crosses the wavelength axis. This process is called *extrapolation*. (See Figure 66.) Thus we ignore the slight tail as being due to other, secondary effects.

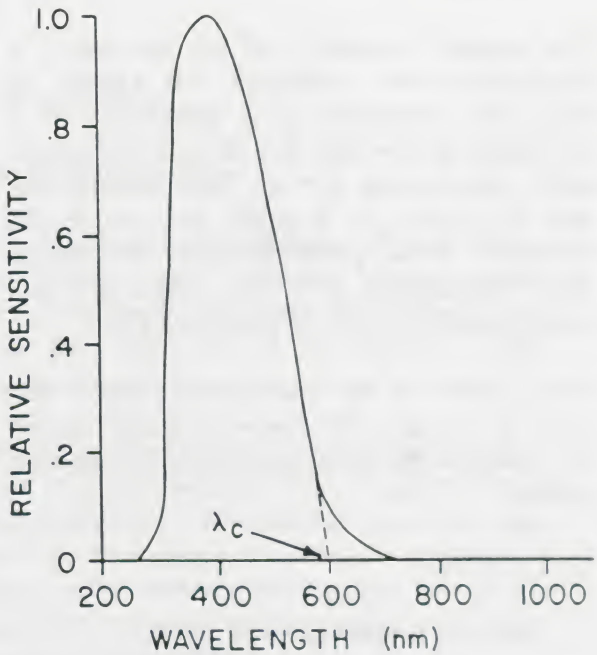


Figure 66. The long-wavelength cutoff is a measure of the work function of the metal.

1. *Extrapolate the spectral sensitivity curve* of the phototube to determine its long-wavelength cutoff λ_c.

2. *Calculate the work-function energy* of the cathode material using the equation $\phi = hc/\lambda_c$. Convert your results to energy in electron volts. Does your result fall in the range of 2 to 5 eV?

The Wave-Particle Paradox

The wave picture of light can account for geometrical and physical optics, and the particle picture can account for the photoelectric effect. The question then is, which picture is the correct one? Is light a wave or a particle? The answer is *neither.* Light is not like any other thing with which we have common experiences.

Since we have no experience with anything exactly like light, we try to develop simple pictures which describe its behavior in familiar terms. The pictures simply serve as a visual reminder of how an unfamiliar quantity (light) acts like something familiar (a wave or a particle) in a particular circumstance.

SUMMARY

The *spectral sensitivity* of the eye and of a *phototube* were measured. To explain in detail the operation of a phototube, it is necessary to view light as a stream of photons, each with energy $E = hf$. Each photon may give its energy to a single electron in the cathode. These photoelectrons can escape with energies up to $hf - \phi$, where ϕ is the *work function* of the cathode material.

This picture of the *photoelectric effect* was used to explain the long-wavelength cutoff $\lambda_c = hc/\phi$ of the phototube's spectral characteristics.

QUESTIONS

1. Is light a wave or a particle?

2. List the wave-like and the particle-like properties of light.

3. How would you measure the spectral sensitivity of a photovoltaic cell?

PROBLEMS

1. For yellow light (500 nm), what is its:

   a. Frequency?

   b. Photon energy?

2. FM radio waves have frequencies around 100 MHz (= 10^8 Hz). What are their:

   a. Wavelengths?

   b. Photon energies?

3. What color light would correspond to the long-wavelength cutoff for a material with a work function of 4×10^{-19} J?

SECTION C

Light and Semiconductors

INTRODUCTION

In this section we begin to explore how semiconductor* light detectors work. We will start with a simple experiment to determine how quickly a particular detector, called a photoconductor, can respond to *changes* in the amount of incident light. The result of this experiment, which measures the *response time* of the device, will give us some clues regarding what goes on in the detector when light strikes it.

A second experiment, using a different but related detector, called a photodiode, will explore the characteristics of *thermal drift* and *dark current.* We will then describe a model of what is happening in these semiconductors when they are struck by light, and we will see how well this model predicts the experimental results. Recalling that the experiments in Section A also used a semiconductor device (a photovoltaic cell), we will use our model to better understand its operation as well.

*A semiconductor may be loosely regarded as a material whose ability to conduct electric current is intermediate between that of a conductor and that of an insulator.

Figure 67. A photoconductor. The dark, snake-like region is the semiconductor. The lighter regions are plated-on metal contacts which connect to the external leads.

The Photoconductor

The *photoconductor* (Figure 67) is a simple, inexpensive, and sensitive semiconductor which changes its resistance when illuminated. You can think of it as merely a light-dependent resistor.

The photoconductor represents the simplest type of semiconductor device, called a "bulk semiconductor." Its internal structure does not vary from place to place, but instead it is more or less uniform throughout. The photoconductor symbol indicates that it is basically a resistor (Figure 68).

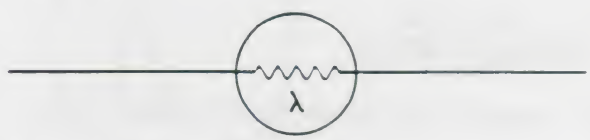


Figure 68. The photoconductor schematic symbol. This device can be thought of as a light-dependent resistor. The λ indicates the sensitivity to various wavelengths of light.

The Photodiode

Unlike the photoconductor, the *photodiode* is a semiconductor whose internal composition does vary from place to place. Like the photovoltaic cell, it is a "junction semiconductor." That is, it is made up of two different types of semiconductor joined together. Each material alone acts like a bulk semiconductor, so that the results of Experiment C-1 will be applicable. However, the presence of a junction region introduces a fundamental difference.

More complicated devices, like the transistor and the silicon-controlled rectifier (SCR), may contain two, three, or even more junctions.

EXPERIMENT C-1. Measuring the Response Time of a Photoconductor

This experiment is to determine how quickly the photoconductor responds when the amount of light illuminating it increases or decreases. The first problem in designing such an experiment is to get a light which can turn on and off very quickly. It is not satisfactory to simply switch on and off a normal incandescent light, because such lights actually take a fairly long time to change–on the order of tenths of a second.

For a light source which turns on and off very quickly, you will use an electronic *stroboscope*. The "strobe" creates very short, repetitive bursts of light. It can turn on and off within a millisecond or less. Since these are rather fast times, an ordinary meter cannot respond fast enough. Instead, the output will be displayed on an oscilloscope (Figure 69).

Experimental Details

The quantity which you need to know is the current i through the photoconductor as a result of a battery voltage applied across it. You will measure i by connecting a resistor R in series with the battery and measuring the voltage V across the resistor. According to Ohm's law:

$$V = iR$$

As long as the resistance R across the resistor is much smaller than the resistance of the photoconductor, the voltage drop V measured across the resistor with the scope is much smaller than the voltage of the battery.

Then the presence of R in the circuit does not seriously change the current through the photoconductor. This voltage V is both amplified by and displayed on the oscilloscope. The scope can respond to extremely rapid changes of the input voltage.

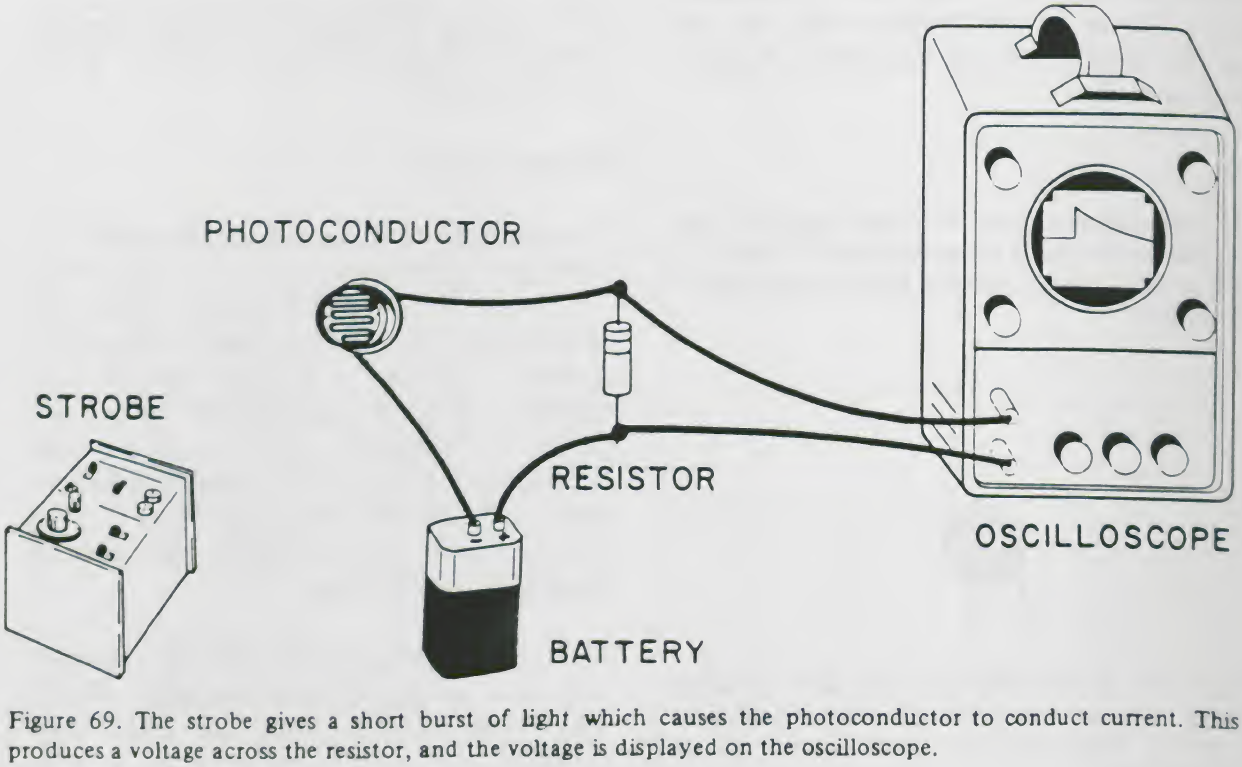


Figure 69. The strobe gives a short burst of light which causes the photoconductor to conduct current. This produces a voltage across the resistor, and the voltage is displayed on the oscilloscope.

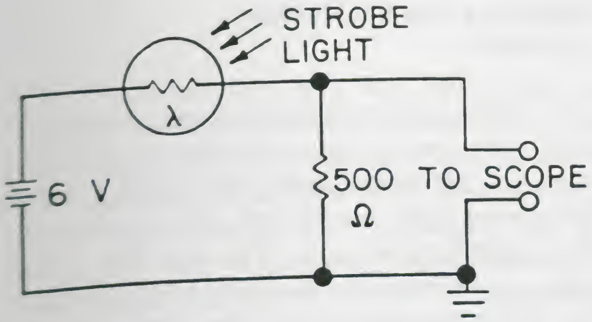


Figure 70. Wiring schematic. The voltage across the photoconductor is greater than that across the resistor.

Procedure

1. *Assemble the detection circuit* (Figure 70). This circuit consists of the photoconductor, the battery, the resistor, and the oscilloscope. Use a 6- or 9-V battery and a 500-Ω resistor. If you do not know how to operate an oscilloscope, see the appendix at the end of the module.

2. *Check the circuit operation*. Before turning on the strobe, check to see that your detection circuit is working. Point the photoconductor so that it can detect the light in the laboratory. Turn on the oscilloscope, and see if you can observe variations in the voltage.

You can probably see variations in V at a frequency of 120 Hz. These are due to the room lights, and they can be quite troublesome if you are trying to measure something else. It will therefore be necessary to conduct the rest of this experiment in darkness, or at least to shield the photodetector reasonably well from the room lights.

3. *Turn on the strobe* so that it flashes about ten times per second. You may have to keep it at least 1 m away from the detector to avoid overloading the detector. In a dark room, it is advisable to aim the strobe at the ceiling or a nearby wall and arrange the photoconductor to detect the reflected light.

4. *Adjust the triggering on the scope*. You should be able to obtain a steady, recurring trace, somewhat like the one sketched in Figure 71. Be sure that you have a scope that can measure DC voltage, and that you are using DC coupling and *not* AC coupling.

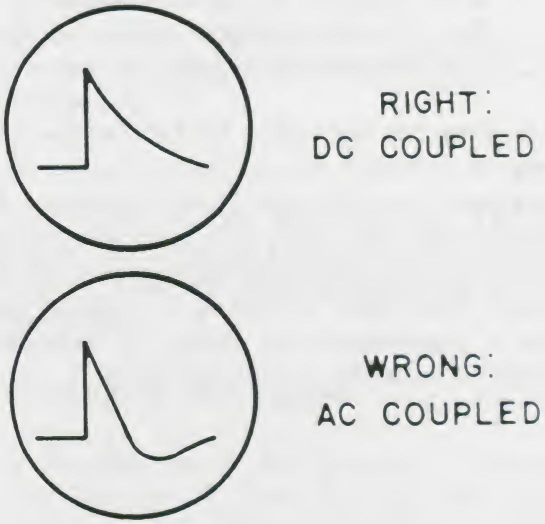


Figure 71. Typical oscilloscope traces observable in this experiment.

5. *Estimate the response time*. Notice that it takes much less time for the photoconductor to turn "on" than it does to turn "off." This is indicated by the fact that the scope trace jumps up much more suddenly than it falls back down. You probably cannot measure how quickly the photodetector does turn on. But can you estimate an upper limit? That is, can you make a statement like the following: "The photoconductor turns on in less than 50 μs"?

A detailed procedure for measuring the time required to turn "off" the photoconductor is described on the next page.

Making a Detailed Measurement

6. *Adjust the oscilloscope* so that a horizontal grid line on the face of the scope represents zero volts, and a vertical line on the left of the grid represents the beginning of the light pulse.

7. *Measure the voltage level* at succeeding times as accurately as you can. Begin with 1-ms intervals. After about 6 ms, begin to space the points out more, so that 10 more readings come out to a total time span of 100 ms.

Adjusting the time base for fast sweeps may help to improve the accuracy of your measurements over the first 10 ms. Increasing the vertical gain may help to increase the accuracy of your measurements for later parts of the signal. See Figure 72 below for typical data for a photoconductor which is somewhat different from the one you are using.

Time (ms)	Reading (Scale Divisions)
0	3.8
1	3.3
2	2.8
3	2.4
4	2.2
5	1.9
6	1.6
8	1.25
10	0.95
15	0.57
20	0.30
25	0.20
30	0.13
50	0.053
100	0.052

Figure 72. Typical data for a photoconductor. Note how the readings are spread out for longer times after 10 ms.

Checking a Possible Problem (Optional)

You might suspect that the longer "turnoff" time you see is not the photoconductor response, but rather is the slow turning off of the strobe light, which the photoconductor then faithfully records. To test this possibility, substitute some other photodetector for the photoconductor. The phototube of Section B is an ideal choice. Bring the strobe closer to compensate for the lower sensitivity of the phototube. Otherwise, repeat the experiment. If your signal is too small to be detected by the scope, increase the battery voltage, the resistance, or both.

Estimating the Decay Time

The time taken for a detector to respond to a sudden increase of light input is called the *rise time*. The time taken to respond to a decrease of light input is called the *decay time*. These can be defined more precisely in various ways. For instance, it is common to measure the decay time as the time required for the output to go from 90% to 10% of its peak value. This is illustrated in Figure 73.

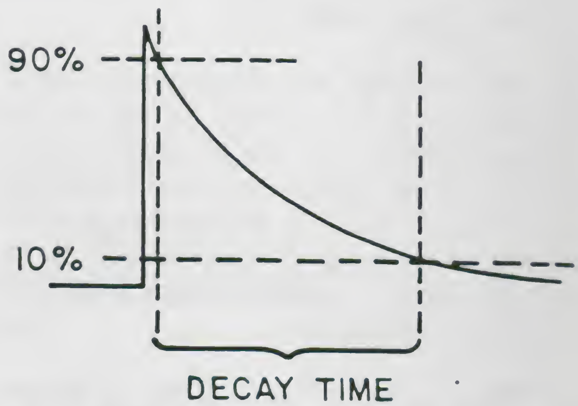


Figure 73. The "decay time" measures the speed of response to a sudden decrease in light input.

8. *Estimate the photoconductor's decay time* from your data. How does it compare to the rise time?

In this experiment you will look at one last property of photodetectors–how their characteristics depend on temperature. Of course, the response of an ideal photodetector is the same regardless of its temperature. But you will find that at least one photodetector, the *photodiode*, is far from ideal. The experiment will also help to verify the model of semiconductors that will be developed later.

About the Photodiode

The photodiode schematic symbol is shown in Figure 74. Like any diode, the photodiode easily passes current in one direction but not the other. It is that "other" direction which will be of primary interest here. The light-dependent current flows *against* the direction of the triangular arrow in the symbol.

Figure 74. Photodiode schematic symbol. Current flows easily in the direction in which the triangle points, but the current in the other direction depends on the light level.

The photodiode is essentially a solid-state version of the phototube (Figure 41). Like the phototube, it permits a reverse current to pass which is proportional to the light shining on it. If there is a lot of light, a large reverse current can pass. If there is no light, there is very little current.

The Dark Current

An ideal photodiode would pass no reverse current when no light was shining on it. Unfortunately, no real device works perfectly. Even when no light shines on the real photodiode, a little current does flow, and it can

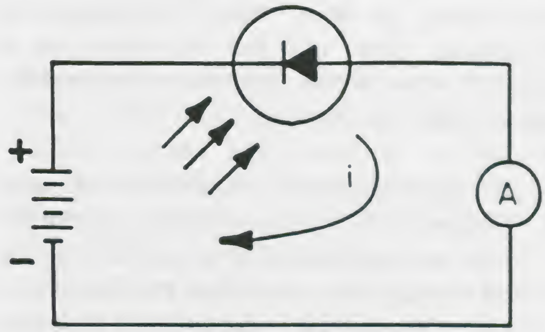


Figure 75. Like the phototube, the photodiode acts as a valve, permitting current to pass in proportion to the light level.

cause errors in light measurements. This current is called the *dark current* (or the *leakage current*), and its study is the object of this experiment.

Measuring the Dark Current

In this experiment it is necessary to prevent any light at all from reaching the diode. Actually, that is not too easy. One of the most effective ways is to "pot" the diode in a casing of opaque plastic. Manufacturers do this to ordinary diodes, using a special black *potting compound* to permanently eliminate any light sensitivity. If they did not, every diode would be a photodiode. You can therefore use an ordinary diode in this experiment, since it is basically the same as a photodiode which is in complete darkness (Figure 76).

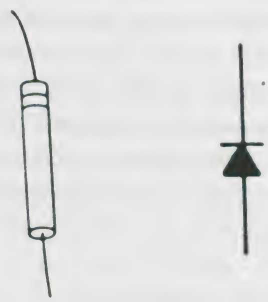


Figure 76. An ordinary diode behaves just like a photodiode in the dark.

Procedure

You will measure the dark current at different temperatures to learn how it depends on temperature. You will put the diode in a beaker of warm water, and measure the dark current as the water cools.

1. *Assemble the circuit illustrated in Figure 77.* The 1-kΩ resistor will keep the diode from burning out if it is hooked up in the wrong direction. The arrow on the diode should be pointing *toward* the positive terminal of the battery. The resulting small current (less than 1 μA) cannot be measured with a simple ammeter. Instead, you will measure the voltage across the 1-kΩ resistor by using a high-gain amplifier and a voltmeter.

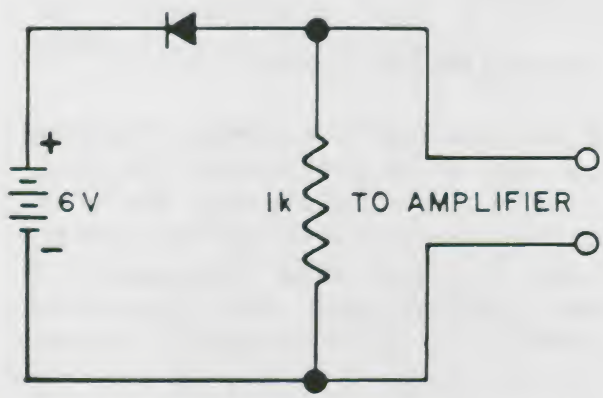


Figure 77. The voltage across a fixed resistor indicates the diode leakage current.

2. *Hook up the amplifier and voltmeter, as in Figure 78.* Turn the amplifier GAIN control all the way up, and set the meter on the 2-V scale. The overall gain is now about 1000, so that a full-scale reading would represent a current of 2 μA in the resistor. The actual current at this stage is much less if things are hooked up properly.

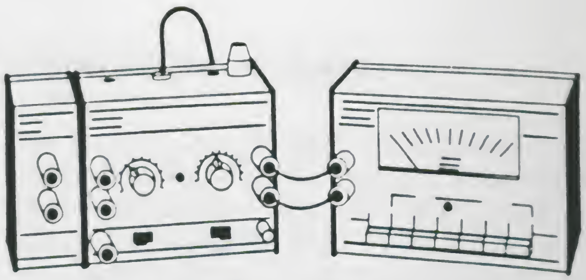


Figure 78. The amplifier (with pre-amp) and meter are used to read the voltage.

3. *Place the diode in hot water.* The diode should first be encased in a plastic bag to avoid having water short-circuit it. The diode *must remain dry* during the measurements. To begin with, the water temperature should be about 100°C.

4. *Re-adjust the amplifier GAIN.* At the new temperature, the meter reading is much greater than before–probably off scale. Turn down the gain so that the reading is nearly, but not quite, full scale.

5. *Check the amplifier OFFSET.* First, disconnect the battery. The reading should be zero on the meter. If not, adjust the offset so the reading is zero. Then reconnect the battery.

6. *Record the meter reading and the water temperature.* Notice that the reading is somewhat arbitrary because of the unknown gain value. This does not matter because all of the following readings will have the correct *relative* values, so long as the gain remains unchanged.

7. *Cool the water by a few degrees, and repeat steps 5 and 6.* This can be done easily by adding a little cold water to the hot water. Stir thoroughly before taking readings.

8. *Repeat steps 5 through 7* down to about 50°C.

So far you have been studying the behavior of photodetectors with a view toward understanding how these devices work. Before analyzing the results, you can apply what you have already learned to see how photodetectors are able to perform practical tasks by controlling other devices. That is the purpose of this last experiment.

Using External Light

Many applications for photodetectors use "external" light, or light which is not itself part of the control system. For example, a decrease in the amount of sunlight in the evening can be used to turn street lights on automatically.

One of the most common photodetector applications is the automatic exposure mechanism in modern cameras. Previously, camera settings were made by hand, using a separate *exposure meter* (Figure 79). Such a meter measures the illuminance, using a photoconductor circuit very much like the one you studied in Experiment C-1. In many modern cameras the exposure meter is built into the camera itself, and its current controls the exposure settings automatically.

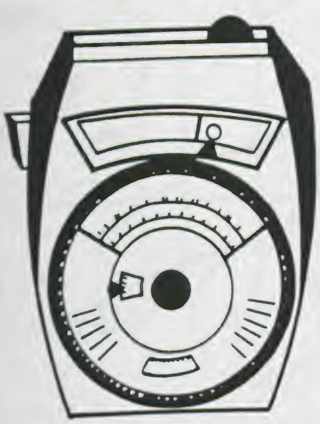


Figure 79. Exposure meters are used to control camera settings based on external light levels.

Using Internal Light

Many other control applications use "internal" light which is generated as part of the control system. For example, an automatic counter for objects passing along a conveyor belt may consist of a light source on one side of the belt and a photocell on the other side. A count is registered whenever an object interrupts the beam between the source and the photocell. Another device which uses internal light is the photoelectric burglar alarm (Figure 80). The alarm is triggered when an intruder interrupts a beam crossing the entryway.

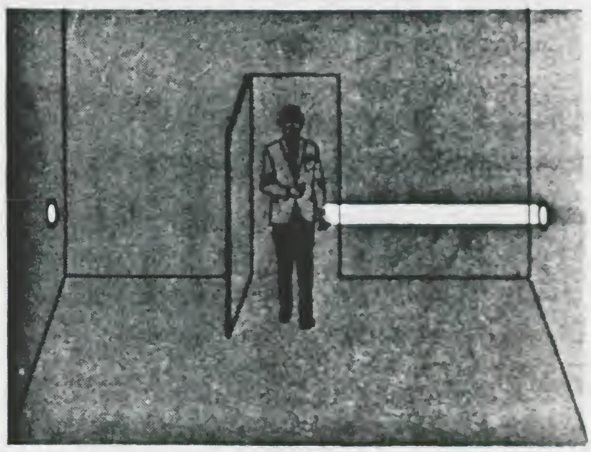


Figure 80. The photoelectric burglar alarm is a control system using internal light.

Building a Burglar Alarm

To get a better feel for how light can be used in a control system, you will build a simple burglar alarm with the photoconductor studied previously. While simple, the circuit involved is quite practical, and it can be used for a variety of applications in addition to this one. The burglar alarm is designed to turn on when the illuminance at the photoconductor goes below a preset level. With a simple interchange of components, the circuit can be altered to trigger when the illuminance increases.

Voltage-Divider Circuit

A basic element in your burglar alarm circuit is a *voltage-divider* circuit (Figure 81). Its purpose is to provide a variable voltage which depends on the light level. In this experiment you will need a voltage which goes from negative to positive when the light level goes down.

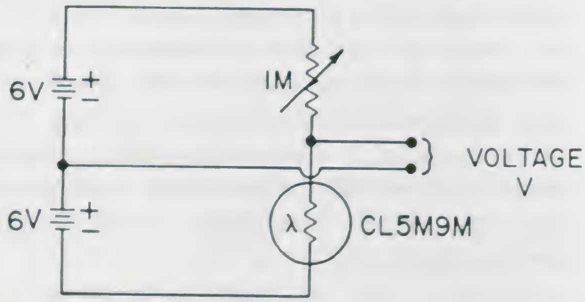


Figure 81. The voltage divider converts changes of resistance into changes of voltage.

This can be accomplished with a divider consisting of the photoconductor in series with a variable resistor, as shown in the figure. The variable resistor is not light sensitive, but its value should be adjustable from 0 to 1 MΩ. The ends of the divider are connected to two 6-V batteries wired in series.

1. *Hook up the voltage divider.* The complete setup for the divider is shown in Figure 82. The power required is obtained from the two batteries. Be sure that the "+" terminal of one is connected to the "–" terminal of the other.

2. *Look at the voltage V on the scope.* As Figure 82 indicates, the scope "ground" lead should be connected to the "common" point, where the batteries are joined together. As in Experiment C-1, be sure to use DC coupling to the scope.

3. *Change the light intensity reaching the photoconductor.* First shine a strong light on it, then turn off the light or place some object in the light path. The voltage *V* should go up when the intensity goes down, and vice versa.

4. *Adjust the variable resistor* until *V* goes from negative to positive when the illuminance goes from high to low. When this is done, any interruption of the light is signalled by the voltage level crossing zero. To make a burglar alarm, you need only an electronic "zero-crossing detector," which can set off a bell or buzzer.

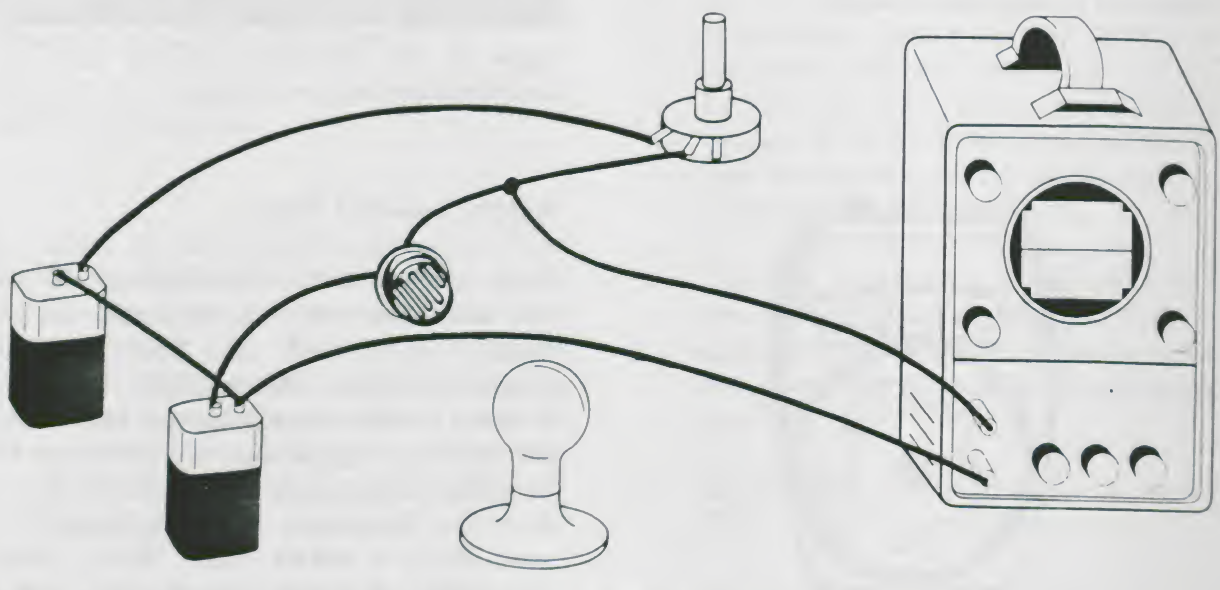


Figure 82. The variable resistor should be adjusted so that the voltage goes from positive to negative when the light is interrupted.

Voltage-Controlled Switch

For a "zero-crossing detector," you can use a *silicon-controlled rectifier* (SCR). This is a semiconductor device which acts very much like an ordinary mechanical switch. It allows current to flow in a circuit whenever it is turned "on." In this case, that current provides the power to operate an audible alarm. The current flows by way of the leads marked A and K in Figure 83.

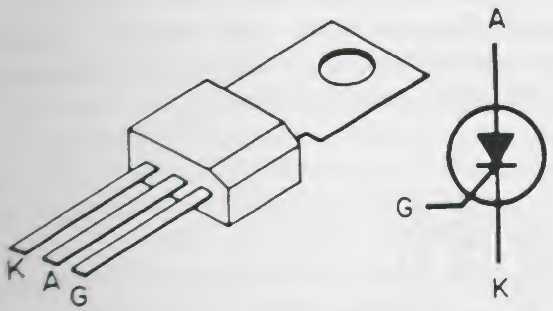


Figure 83. The SCR has a gate G which can be used to switch on the current from A to K.

The difference between the SCR and a mechanical switch is that you do not flip a handle from one position to another to turn it on, but instead apply a suitable voltage to the "gate" (lead G). Once the SCR is switched on, it remains on until the current is interrupted by some other means. Thus an alarm will continue to sound even after the intruder flees.

Complete Burglar Alarm

5. *Hook up the circuit shown in Figure 84.* The voltage-divider circuit remains unchanged. Basically, all that you do here is to replace the scope with leads G and K from the SCR. Then connect the buzzer between the SCR lead A and the 6-V battery terminal. The reset switch is optional; without it, it will not be as easy to turn off the buzzer.

6. *Try out your burglar alarm.* With a strong light shining on the photoconductor, the alarm should remain silent after being reset. If not, adjust the variable resistor as necessary. Then, when the light is interrupted, the alarm should come on and stay on. If the alarm does not stay on, it may be necessary to bypass the buzzer with a capacitor, as the dotted portions of Figure 84 indicate.

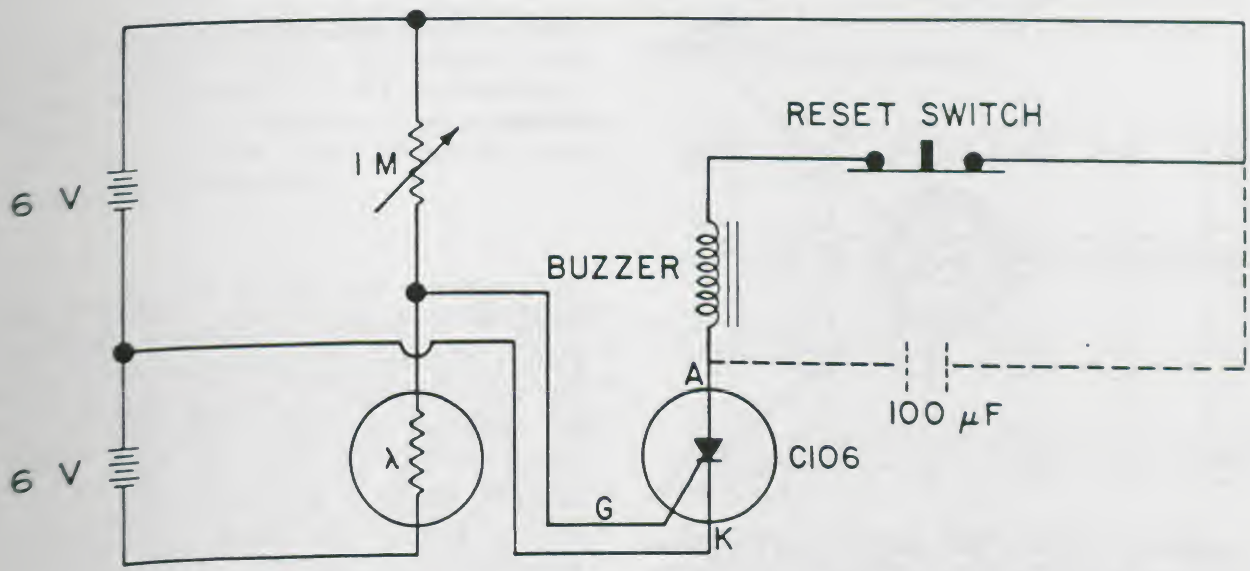


Figure 84. To turn the alarm on, the control voltage from the voltage divider is applied to the gate of the silicon-controlled switch.

STRUCTURE OF SEMICONDUCTORS

The "solid-state" photodetectors you have studied–photovoltaic cells, photoconductors, and photodiodes–are all *semiconductor* devices. Transistors, integrated circuits, and dozens of other solid-state components are based on the same physics. Our discussion must be quite brief, and some of its features would be modified in a more thorough treatment. We will focus attention on the semiconductor elements, such as silicon (Si) and germanium (Ge), rather than on semiconductor compounds, such as cadmium sulfide (CdS).

Atomic Structure

As you may recall from chemistry, each atom of an element has a small, dense, positively charged nucleus. Surrounding the nucleus is a much more widely separated collection of electrons, each with a negative charge. The number of electrons, which is the same as the number of positive charges in the nucleus, is what determines the chemical properties of the atom. Scientists now picture this collection of electrons as a "cloud" of negative charge which is bound to the positive nucleus by electrical forces.

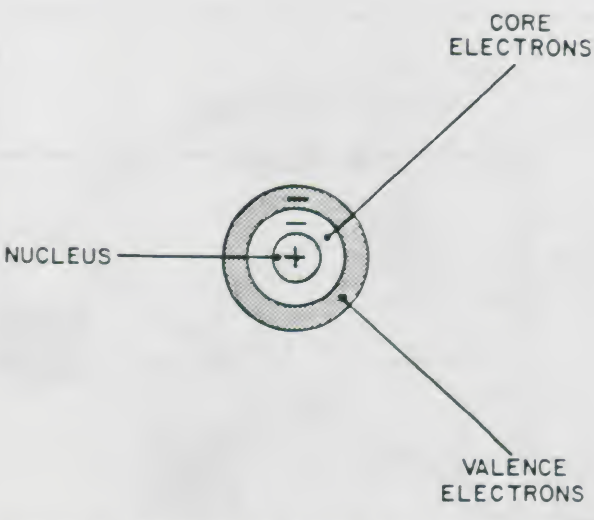


Figure 85. An atom has a small nucleus surrounded by two groups of electrons, which comprise the "electron cloud."

The electron cloud can be divided into two fairly distinct parts (Figure 85). There is an inner group of *core electrons*, which are "tightly" bound and relatively close to the nucleus. A cloud of *valence electrons* is farther removed and less strongly attached to the nucleus.

Semiconductor Atoms

The number of valence electrons is one of the most important characteristics of an atom. The semiconductor elements–principally Si and Ge–each have *four* valence electrons (Figure 86), and it is this number which gives them their special properties.

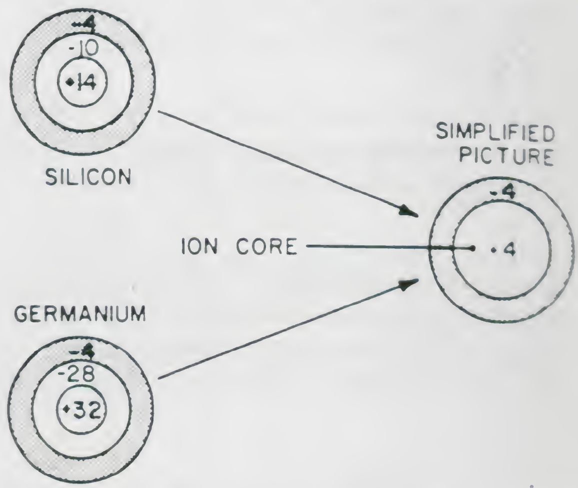


Figure 86. Semiconductor elements each have four valence electrons. In a simplified picture, different semiconductors can be represented in identical fashion.

To emphasize the role of the valence electrons, it is helpful to adopt a simplified picture of atoms. In this picture, the nucleus and core electrons are lumped together into an "effective ion core." The net positive charge of the ion core just balances the negative charge of the valence electrons. In such a picture, the various semiconductor elements appear identical, as Figure 86 emphasizes.

Semiconductor Crystals

In a solid, the atoms generally arrange themselves in a regular pattern or *crystal structure*. The neighboring atoms in the crystal are packed rather tightly together. Thus the valence electron clouds become greatly distorted. Different valence clouds may overlap so much that it becomes difficult to say to which atoms they belong. In this sense, there is a kind of "sharing" of electrons between atoms.

Figure 87 illustrates the situation for a fictitious two-dimensional crystal. Each atom here has four nearest neighbors, which lie at the corners of a square, with the given atom at the center. The distortion of the valence electron clouds is indicated. This distortion is caused by the attractive electrical forces between the electron clouds and the closest (nearest-neighbor) positive ion cores.

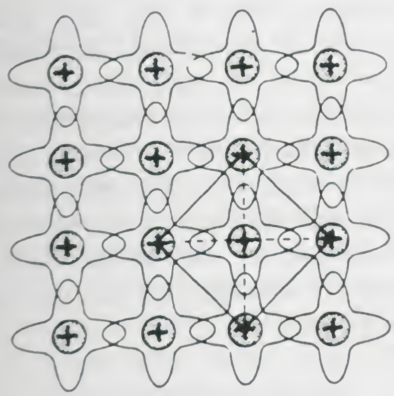


Figure 87. A square pattern of atoms. The distortion of valence electron clouds toward the nearest neighbor atoms is indicated.

The atomic pattern of a semiconductor crystal is not this simple, of course. For one thing, it is three-dimensional. However, each atom does have exactly four nearest neighbors. These lie at four alternate corners of a cube, with the given atom at the center (Figure 88). The pattern is called the *diamond crystal structure*, because the carbon atoms in a diamond are arranged the same way.

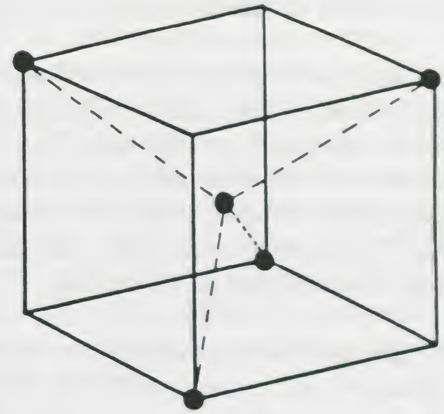


Figure 88. In a semiconductor crystal, each atom has four nearest neighbors. (Only atomic centers are shown.)

Covalent Bonds

The reason for the diamond structure is that, in effect, each semiconductor atom prefers to have *eight* valence electrons rather than the actual number, four. That can be achieved if each atom shares its valence electrons with neighboring atoms. Such "cooperation" leads to a chemical bond between atoms called a *covalent bond*.

The situation is represented schematically in Figure 89, again using the two-dimensional crystal. The various valence electrons are shown as dots to make counting them easier. Although the total number of electrons per atom is still four, the average number in the vicinity of each ion core has been increased to eight by covalent bonding.

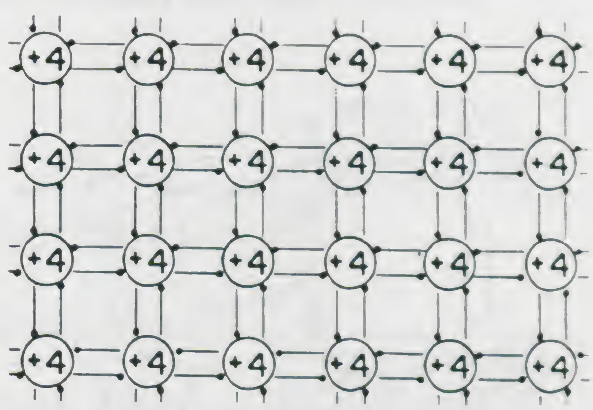


Figure 89. By sharing valence electrons, atoms can increase the number of electrons in their vicinities from four to eight.

CONDUCTION IN SEMICONDUCTORS

Electric current is a net flow of charge in a material. Metals are good conductors of current because they contain many electrons which are not bound to any particular atom and can move readily when a voltage is applied. These electrons are called *conduction electrons* or sometimes *free electrons*.

At first glance, there would appear to be *no* free electrons in a semiconductor, because each electron is used to form a covalent bond between two atoms. With no free electrons, such a crystal should be a poor conductor, even an *insulator*. This conclusion is not wrong: at temperatures *near absolute zero* a pure crystal of Si or Ge *is* an insulator.

Thermal Activation of Conduction Electrons

However, at higher temperatures the crystal structure begins to vibrate. These vibrations produce a certain amount of "damage," which increases as the temperature is raised. When the temperature gets high enough, the thermal vibrations shake the crystal structure completely apart and melting occurs. At room temperature, no thermal effects are visible, but significant effects do occur on the atomic scale.

One form of "damage" to a semiconductor crystal is the breaking of covalent bonds. When this happens, valence electrons are shaken loose and become free for a time. As free electrons they can then participate in the conduction of current. This process is called *thermal activation* of conduction electrons. (See Figure 90.)

Creation of Conducting Holes

When a conduction electron is created and moves away, a deficiency of negative charge is left behind. Such a region is called a *hole*. A hole may be regarded as having a positive charge, since the missing electron no longer balances out the local core charge. For every conduction electron created, a hole is also created, so it is common to speak of *electron-hole pairs*.

A hole can also move around and make its own contribution to the electrical current. This happens when a *valence* (not conduction) electron fills in the hole and leaves another hole in an adjacent location (Figure 91). However, it is much easier to treat the motion of the positively charged hole than of the valence electrons. To some extent the situation is similar to the motion of an air bubble in a liquid. It is much easier to think of the motion of the bubble than of the motion of all the liquid molecules that must move out of the way.

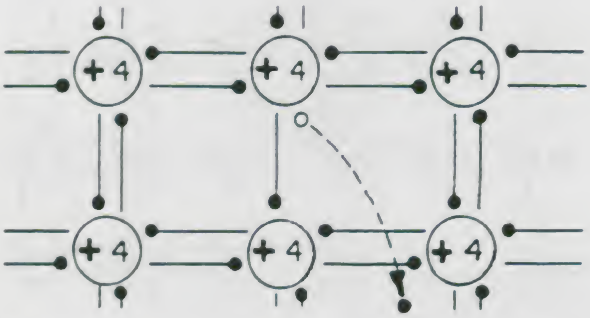


Figure 90. Conducting electrons are created by the breaking of covalent bonds in a semiconductor.

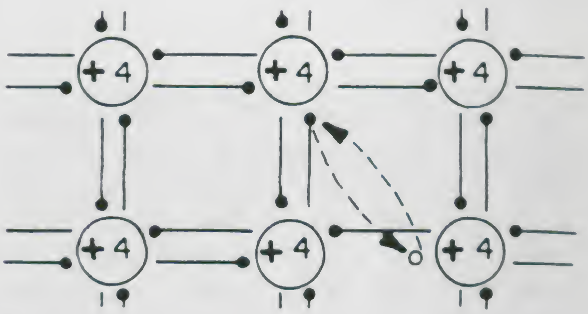


Figure 91. Holes can move by the transfer of valence electrons between bonds.

Limitations of the Atomic Picture

This atomic picture of the structure of semiconductors, and of the conduction process, is not an entirely accurate one. The reason is that the nature of electrons (and all other particles) is such that it is not possible to specify *exactly* where an electron is at any particular instant of time.

For the semiconductor crystal, this means that one cannot say which valence electrons are associated with which atom, or from which atom a conducting electron came. A single conducting electron (or a hole, for that matter) is in some sense "spread" over thousands of atoms in the crystal. The more localized picture which we have described serves only as a convenient visualization of the processes involved.

The Energy Picture

A more accurate picture of the conduction process can be presented in terms of the energies of the valence electrons. As you may know, an electron in an isolated atom cannot have any and all possible energies. Rather, there are only certain specific "allowed" energies. Further, no two electrons in the atom can be in the same *energy state*. This is stated in the *Pauli Exclusion Principle*.

When atoms bind together into a crystal, the allowed energy states for the valence electrons broaden out into *bands* of energy. But there are still certain energies which an electron cannot ever have. And again, no two electrons in the crystal can be in the same energy state. It is on the basis of these allowed and disallowed energy states, and the Exclusion Principle, that the different properties of conductors, insulators, and semiconductors must be explained.

Energy-Level Diagrams

Figure 92 shows an *energy-level diagram* for a conductor, an insulator, and a semiconductor. This is *not* a graph in the ordinary sense, since the horizontal axis has no significance. Instead, it illustrates the possible energy states which the electrons in the material can have. Note that in each case the possible energy states are divided into two groups, or bands, of energy states. These are the *valence bands* and the *conduction bands*, with an *energy gap* of disallowed energies between.

At the absolute zero of temperature, the electrons will fill up all of the lowest energy states (with no two occupying the same state). For the conductor, this process results in only a partially filled set of valence states. For the semiconductor and the insulator, the valence states are all *exactly* filled, and there are no electrons in the conduction states.

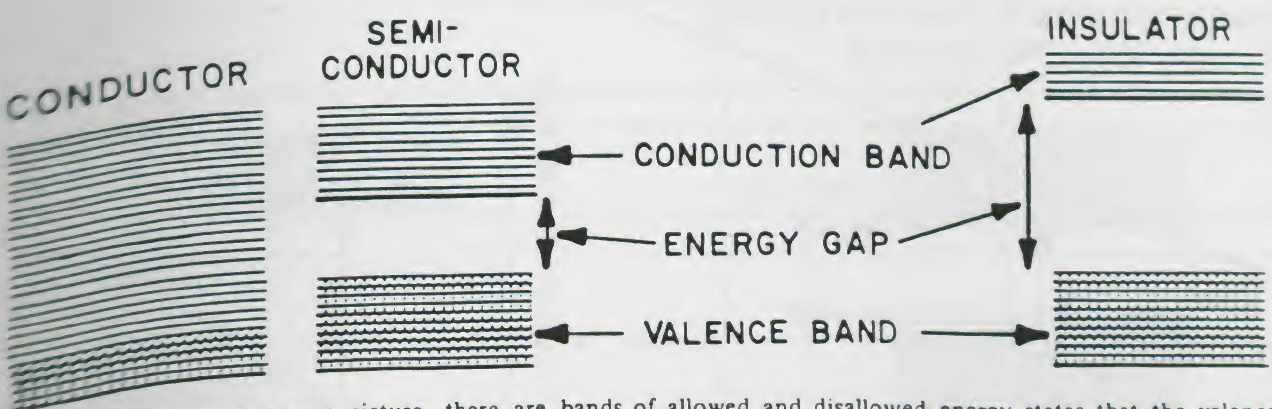


Figure 92. In the energy picture, there are bands of allowed and disallowed energy states that the valence electrons can be in. At absolute zero the electrons fill all the lowest energy states.

Electrical Conduction

Applying a voltage to a material to produce an electric current is equivalent to giving the electrons a small amount of energy. That is, it is the same as putting them in slightly higher energy states. For conductors, this is possible: the conduction band overlaps the valence band, and there are many empty states of slightly higher energy for the electrons to go to. When a voltage is applied to a conductor, the electrons get accelerated into these empty energy states and a current flows.

For an insulator, the energy added by a voltage is considerably less than the energy gap. Since all of the valence energy states are filled, there are no empty states with slightly more energy for the valence electrons to go into. Consequently, when a voltage is applied, the electrons as a group cannot accept the higher energy of acceleration and no current will flow.

At absolute zero, semiconductors behave as insulators. But at higher temperatures, as stated earlier, thermal vibrations produce electron-hole pairs that can participate in current flow. In the energy-level picture, this is equivalent to giving some of the valence electrons energies equal to or greater than the energy gap. This puts them into the conduction band (and simultaneously leaves holes in the valence band). In the conduction band there are many unoccupied states for the electrons to go into when a voltage is applied. The higher the temperature, the more electrons in the conduction band, and the greater the conductivity. (See Figure 93.)

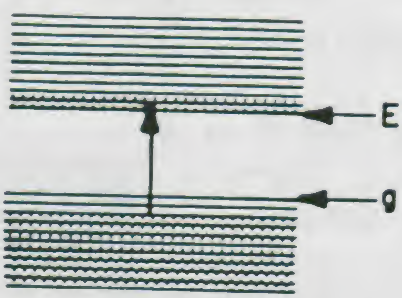


Figure 93. In a semiconductor, thermal activation raises some electrons from the valence band into the conduction band so that an electric current can flow.

For insulators, however, the energy gap is so large that few electrons get enough energy by thermal activation to get into the conduction band. As a result few electrons can accept the higher energy from an applied voltage and there is little electrical conduction.

From this energy picture of conduction, we see that the special properties of semiconductors are based on two properties of atomic electrons:

> The electrons of an atom can be only in certain specific energy states.
>
> No two electrons can be in the same energy state at the same time (the Pauli Exclusion Principle).

Photoactivation of Electrons

Besides the thermal activation of conduction electrons, there are other processes in semiconductors which can raise the energy of an electron from the valence band into the conduction band, thus leading to an increase in the conductivity (a decrease in the resistance). (See Figure 94.) For instance, light shining on a semiconductor crystal can cause *photoactivation*. In effect, photons in the light beam collide with valence electrons and give them energy. In order for this process to raise an electron into the conduction band, the photon energy ($E = hf$) must exceed the energy gap E_g.

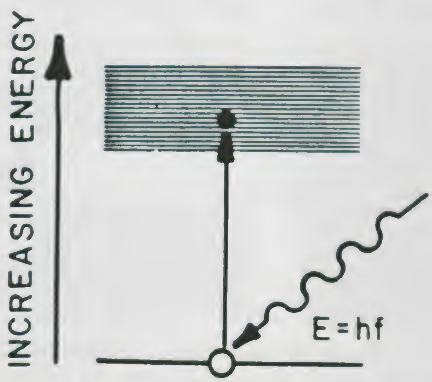


Figure 94. A "collision" with a photon can activate an electron across the energy gap.

PHOTOCONDUCTOR CHARACTERISTICS

This energy picture of semiconductors can be used to explain some of the main characteristics of solid-state photodetectors. The *photoconductor* is a good device to start with, since it comes closest to being as simple as the model.

The photoconductor is a "bulk semiconductor," with no "junctions" to complicate matters. Essentially, it is just a single semiconductor material, arranged so that light can fall on it. The light creates electron-hole pairs which are free to carry current if a voltage is applied to the device. The resistance R is defined as the voltage divided by the current. The resistance decreases as the number of electron-hole pairs increases, and vice versa.

Response to Total Illumination

The number of electron-hole pairs depends on the number of photons striking the semiconductor. Since the number of photons is proportional to the illuminance, the resistance and the illuminance should be *inversely proportional* to each other. As an equation, this relation is written:

$$R = k/L$$

where the constant of proportionality k depends on the area exposed, the type of material, etc.

Figure 94 shows the actual sensitivity curve for a photoconductor of the type used in your experiments. To increase the range covered, the graph is shown as a "log-log" plot. As expected, the graph shows that decreasing the illuminance by a certain factor, such as ten, increases the resistance by the same factor. Such behavior persists down to quite small values of the illuminance. (For comparison, see Tables III and IV.)

It should be noted that, for sufficiently small illuminance, this simple relation must fail. After all, even in total darkness there are thermally activated electron-hole pairs, so the resistance does not ever become infinite. Furthermore, most real photoconductor materials contain chemical impurities, crystal structure defects, and so on, which result in some free carriers of current under any circumstances.

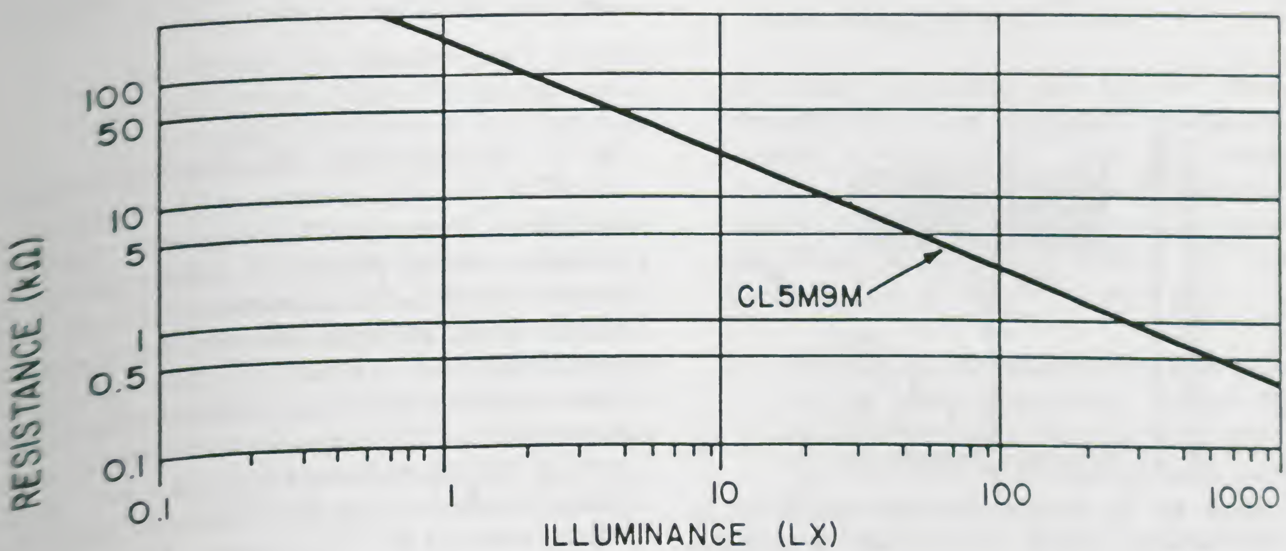


Figure 95. Over a large range of light levels, the photoconductor resistance is inversely proportional to the illuminance.

Speed of Response

In Experiment C-1 you found that the photoconductor can respond quite rapidly to a sudden increase in illuminance. When the illuminance was reduced suddenly, the resistance decreased relatively slowly to its original value. You can understand these results for the response time as follows.

When the rate of photon bombardment is increased, the production of electron-hole pairs also increases right away. While it may take the resistance some time to reach a new *equilibrium* value, some response is seen almost at once. On the other hand, when the photon bombardment is halted, the pairs already created do not disappear instantly. They disappear gradually, so the resistance increases relatively slowly.

This latter effect results from the fact that, in a bulk semiconductor, the main way to get rid of excess pairs is through the *recombination* of electrons and holes (Figure 96). This process is the opposite of pair formation. When an electron and a hole accidentally cross paths as they wander, the electron "fills in" the hole and becomes a bound electron once more. As the concentration of holes and electrons decreases, it takes longer and longer for remaining pairs to "find" each other. Therefore, the recombination process slows down as time passes.

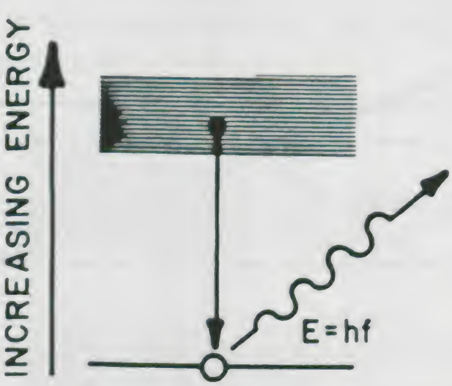


Figure 96. An electron and a hole can vanish by recombination. Energy (possibly light) is released in this process.

Spectral Response

As you learned earlier, each photodetector responds with a different sensitivity to different colors of light. The *spectral response curve* for your photoconductor (Figure 97) looks much like the curves discussed previously for the eye and the phototube. In particular, the maximum sensitivity for this photoconductor occurs at a wavelength of about 550 nm, which is the same as for the eye. Thus the material in this photoconductor is especially suitable for use in photographic light meters.

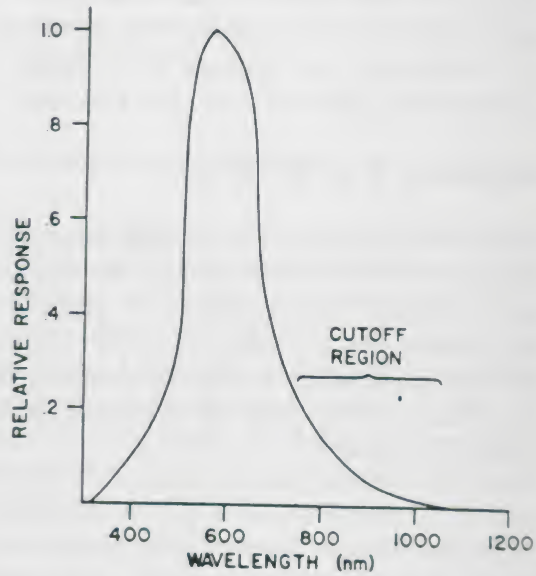


Figure 97. The spectral response can be used to estimate the energy gap of a photoconductor.

As for the phototube, the long-wavelength cutoff of the spectral response of the photoconductor represents the minimum energy necessary for a photon to release a conduction electron. The observed cutoff is not ideally sharp, probably because of non-ideal crystal structure. Therefore, the interpretation of the cutoff in terms of an energy gap is somewhat ambiguous. However, the curve can be used to estimate the energy gap, and the value obtained can be compared with the values obtained by other means. That is our next topic.

ESTIMATING THE ENERGY GAP

You can estimate the energy gap in a semiconductor photodetector by using two different methods. These methods involve first the long-wavelength cutoff of the spectral response and, secondly, the "thermal drift" of the dark current.

You have not actually measured the spectral response of any semiconductor device in your experiments. However, the spectral response of a silicon photovoltaic cell was given and briefly discussed in Section B. In Experiment C-2, you did determine the dark current dependence on temperature for a silicon diode. Using these results, you can estimate the energy gap in silicon by both methods.

Spectral Cutoff Method

The major problem in using this method is to determine what wavelength should be taken as the cutoff value. Given the cutoff value, the remaining calculations are extremely simple. Probably the best way to choose the cutoff wavelength λ_c is to *extrapolate* the rapidly decreasing portion of the spectral response curve to the horizontal axis. Figure 98 illustrates the procedure, using a hypothetical photoconductor response curve. The dotted line shows the extrapolation, giving $\lambda_c \approx 750$ nm.

1. *Extrapolate the spectral curve for the silicon device* (Figure 57). Record the λ_c you obtain for silicon on the Data Page at the end of the module.

The use of this extrapolated cutoff value assumes that the overall spectral cutoff of a given semiconductor device is not sharp because of small defects in the crystal structure. These could be caused by chemical impurities in the material, for example. Since we are interested in properties of the major portion of the material, we can presumably ignore the long "tail" of the curve due to the remainder.

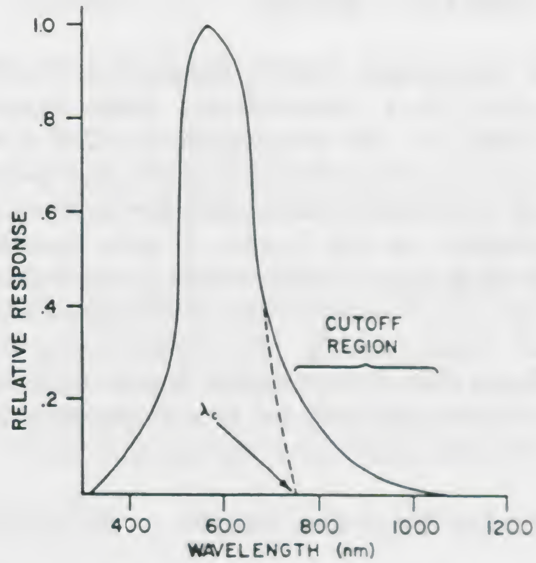


Figure 98. The long-wavelength cutoff is obtained by extrapolating the steep portion of the response curve.

From the value of λ_c we may now calculate a cutoff frequency f_c by dividing λ_c into the speed of light, 3.0×10^8 m/s. Using $\lambda_c = 750$ nm, we obtain:

$$f_c = \frac{3.0 \times 10^8 \text{ m/s}}{750 \times 10^{-9} \text{ m}}$$

$$= 4.0 \times 10^{14} \text{ Hz}$$

2. *Calculate the cutoff frequency for silicon, using your value for λ_c.*

To obtain the energy gap E_g, the cutoff frequency should be multiplied by Planck's constant, $h = 6.6 \times 10^{-34}$ J/Hz. The reason for doing this was discussed in Section B in connection with the behavior of the phototube. Using the example, $f_c = 4.0 \times 10^{14}$ Hz, we obtain $E_g = 2.7 \times 10^{-19}$ J = 1.7 eV.

3. *Calculate E_g for silicon, using your value for the cutoff frequency.* Record this value on the Data Page for comparison with the value to be derived next, using the second method.

Thermal Drift Method

In Experiment C-2 you found that the dark current in a semiconductor diode depends strongly on the temperature, T. This is because the probability of thermal electron-hole pair production increases as the temperature increases. As the number of pairs increases, the dark current also increases proportionally. This fact provides another method for finding the energy gap E_g. The method relies on a theory that shows how the degree of thermal activation depends on the temperature and the energy gap.

Semilog Plot of Dark Current

In order to find the thermal activity, one must turn to the science of *statistical mechanics*, which deals with the analysis of the behavior of a very large number of particles such as atoms or molecules in a solid. By making use of a fundamental relationship known as the *Boltzmann distribution law*, the dependence of the dark current on the temperature and the energy gap can be found. The relationship is:

$$\log i = C - 0.217 E_g/(kT)$$

This says that the logarithm (base 10) of the current varies as the inverse of the (kelvin) temperature. C is just a constant which need not concern us, and $k = 1.38 \times 10^{-23}$ J/K is the *Boltzmann constant*, one of the basic constants of nature.

If this expression is used to plot $\log i$ versus $1/T$, the result is a straight line, as in Figure 99, with a slope given by the coefficient of $1/T$: $(-0.217 E_g/k)$. Therefore, by plotting $\log i$ versus $1/T$ from your data and measuring the slope of the resulting line, you can find the energy gap, E_g.

1. *Convert your temperature values to kelvins.* This can be done by adding 273 to each temperature in degrees Celsius.

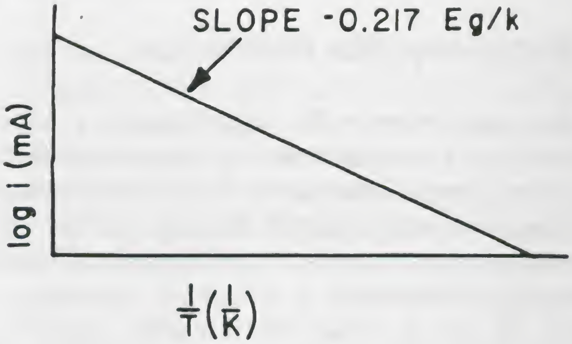


Figure 99. The energy gap can be found from the slope of log i versus the temperature.

2. *Make a graph of log i versus 1/T.* Draw the best straight line you can through the points. (You can find log i from a table of common logarithms.)

3. *Determine the slope of your straight line.* (In this case the slope is the negative of the following ratio: the value of $\log i$ at the point the straight line crosses the vertical axis divided by the value of $1/T$ where it crosses the horizontal axis.)

4. *Calculate E_g from the slope.* If the slope is m, then $E_g = -k \cdot m/0.217$. How does this value for E_g compare with your previous estimate?

SUMMARY

In this section you explored the behavior of *semiconductor* photodetectors. You first examined the speed of response of a *photoconductor* to changes of the illuminance. You measured the *decay time*, and found that this is quite long—perhaps 0.15 s, or even longer. By contrast, the phototube studied in Section B has a very short decay time.

In a second experiment, you found that the *dark current* in a semiconductor photodiode increases rapidly as the temperature increases. You measured this *thermal drift* of the dark current, using an ordinary diode, which be-

haves similarly. Finally, in a third experiment, you saw how a photodetector can be used as a *control device* to accomplish practical tasks. You built a burglar alarm using the photoconductor of Experiment C-1.

Following the experiments, a simple picture of semiconductor structure was presented to explain basic features of your observations. The *covalent bond* between atoms and the *diamond crystal structure* for semiconductor elements were discussed. The concept of *free carriers* of electric charge was introduced. These are created in a semiconductor by *thermal activation* of *electron-hole pairs*. The *energy gap* for the activation process was defined, and this was illustrated using an *energy-level diagram*. The diagram was also used to illustrate *photoactivation* of free carriers, on which the use of semiconductors as photodetectors is based.

Photoconductor characteristics were then discussed qualitatively, using the foregoing simple picture. In particular, the *long-wavelength cutoff* of the *spectral response curve* was recognized as a consequence of the energy gap. This led to an estimate of the gap in silicon from a determination of the cutoff wavelength λ_c. A second method for estimating the gap was also employed, based on the dark current data for a silicon diode.

QUESTIONS

1. Why is the turn-on response of the photoconductor so fast? Why is the decay time relatively so long?

2. Explain in your own words:

   a. Two ways holes may be created.

   b. How a hole moves.

   c. How a hole can be destroyed.

   d. Why a hole is considered as a positive charge.

3. What is the conductivity of a pure semiconductor at very low temperature? Why? Is it still light sensitive?

PROBLEMS

1. Suppose that a certain diode's dark current doubles between 27°C and 77°C. What is its energy gap?

2. From your answer to the previous problem, estimate the cutoff wavelength λ_c for the photodiode.

3. A manufacturer offers a photoconductor whose long-wavelength cutoff occurs at 750 nm. What is the energy gap?

4. An *electron volt* (eV) is a convenient unit of energy. An energy in electron volts is just the value in joules divided by the electron charge in coulombs (1.60×10^{-19} C). What is the energy in eV of an infrared photon of wavelength 1000 nm?

DATA PAGE

EXPERIMENT A-1. Measuring Light with Your Eye

Comparing Sources Directly

A 40-W lamp is ________ times brighter than a candle.

Comparing Illuminations

Distance from 40-W lamp ________.

Distance from candle ________.

Ratio of intensities ________.

DATA PAGE

EXPERIMENT A-3. Measuring Light with a Photovoltaic Cell

Comparing Sources Directly

Meter Reading

	Selenium	Silicon
40-W lamp	100 μA	100 μA
Candle		

Ratio of Meter Readings

Selenium	
Silicon	

Comparing Illuminations

Distance

	Selenium	Silicon
From 40-W lamp		
From candle		

Ratio of Intensities

Selenium	
Silicon	

Actual Rated Output

40-W lamp ________.
Candle *1 candela*

Ratio of intensities ________.

DATA PAGE

EXPERIMENT A-4. Measuring Photovoltaic Properties

Standard source intensity ________.

Output versus Distance

Selenium

Output μA	Distance cm		
100			

Silicon

Room Illumination ________

DATA PAGE

EXPERIMENT A-5. Measuring Solar Power Output

Silicon

R (ohms)	V (volts)	P (watts)

Area of Cell ________.

Selenium

R (ohms)	V (volts)	P (watts)

Area of Cell ________.

EXPERIMENT B-1. Spectral Sensitivity of the Eye

Viewing the Spectrum

Boundary	Position mm
end–violet	
violet–blue	
blue – green	
green – yellow	
yellow–orange	
orange–red	
red–end	

Estimating Spectral Brightness

Position mm	Relative Brightness	Relative Sensitivity

DATA PAGE

EXPERIMENT B-3. Spectral Sensitivity of a Phototube

Position mm	Meter Reading	Relative Sensitivity	Normalized Sensitivity

Long-wavelength cutoff, λ_c = ________mm.

Work function, ϕ = ________ J.

= ________ eV

DATA PAGE

EXPERIMENT B-4. (Optional) *i-V* Characteristics of a Phototube

Anode Voltage V	Photocurrent μA	Photocurrent μA	Photocurrent μA	Photocurrent μA

Illumination ________ ________ ________ ________

DATA PAGE

EXPERIMENT C-1. Measuring Response Time of a Photoconductor

Time ms	Reading scale divisions

DATA PAGE

EXPERIMENT C-2. Measuring Thermal Effects in a Photodiode

Temperature °C	Meter Reading

APPENDIX: The Oscilloscope

The oscilloscope is nothing more than a very fast "graphic machine." It is able to present graphs of voltages (usually on the vertical axis) against time or other voltages (on the horizontal axis). Thus the scope displays the size, shape, and frequency of an input signal. How the oscilloscope circuits are designed is not important for this module. Instead, we shall examine the functions of the external controls which are common to most general-purpose laboratory oscilloscopes. Because most oscilloscopes have additional features and because the naming of controls varies among oscilloscopes, the operating instructions for a specific oscilloscope should always be consulted before use. (The terms scope and oscilloscope are used interchangeably here.)

Some of the basic controls found on all oscilloscopes are listed below, along with a brief explanation of their functions. As you read the description of each control, you should refer to the one on your scope.

I. Screen Section

A. The AC ON/OFF control turns the oscilloscope on. It is usually combined with either the INTENSITY control or the SCALE ILLUMINATION control. Most scopes have a panel light to indicate when they are on.

B. The INTENSITY control changes the brightness of the spot (or trace). If a bright spot is left in one place on the screen for too long, it can "burn" away the phosphor on the screen, leaving a permanent dark spot. For this reason, the intensity is usually kept as low as is consistent with good viewing.

C. The FOCUS control adjusts the sharpness of the trace. It should be adjusted to give the narrowest line possible.

D. The VERTICAL and HORIZONTAL POSITION controls change the up-down and left-right positions of the beam. On some scopes, you may find a BEAM FINDER button, which allows immediate location of a beam which is "off the screen." After finding the beam with the beam finder, you can then use the positioning controls to move the beam to the center of the screen.

II. Vertical Amplifier Section

E. The voltage to be analyzed is usually connected to the VERTICAL INPUT. If there is a *probe* provided with the scope, be sure to check its *attenuation factor.* Most probes are designed to reduce the voltage input to the scope by a factor of ten or more. Any calculation of voltage should include this factor.

F. The VOLTS/CM (also called VERTICAL SENSITIVITY) control allows measurement of the size of a voltage signal. The face of most oscilloscope screens is covered with a grid which is ruled in centimeters. This grid is used to read the voltage of a signal. For example, suppose the trace is 2.5 cm high and the VOLT/DIV is set on 10 VOLTS/CM. Then the voltage input to the scope is 2.5 cm X 10 VOLTS/CM or 25 V. (On many scopes, a concentric control knob allows the vertical sensitivity to vary. For calibrated readings this knob must be properly set.)

III. Time Base Section

G. The TIME/CM control (also called the SWEEP RANGE SELECTOR) varies the rate at which the trace "sweeps" across the oscilloscope screen. This feature is necessary to allow measurement of the duration

of a signal or of the frequency of the signal. For example, if a voltage pulse is 4 cm long and the TIME/CM switch is set on 20 ms/cm, the time required for the pulse is 4 cm X 20 ms/cm or 80 ms. (On many scopes a *multiplier* switch allows the calibration time to be changed by some factor.)

H. A SYNC (synchronization) control is part of the time base section on many inexpensive scopes. Its purpose is to cause the sweep voltage to always begin at the same point of a recurrent signal so the signal appears to "stand still." The SYNC control is turned until the pattern on the screen appears stationary. If you cannot "stop" the signal, you may need to choose a different sweep rate.

I. The SYNC SELECTOR control selects one of three possible *modes of synchronization.* On INTERNAL SYNC, the sweep of the scope is synchronized with the input signal. On EXTERNAL SYNC, the sweep is synchronized with an external signal; on LINE SYNC, the sweep is synchronized with the AC line voltage. This control is usually set to INTERNAL.

J. On more sophisticated scopes, the TRIGGER controls achieve synchronization. Triggering means that the horizontal sweep is caused to begin (triggered) whenever the input signal reaches a predetermined value.

The following exercise is to acquaint you with the controls of the oscilloscope you will use in the Photodetector module. You will need to consult the operating manual for your scope. If you have problems, consult your instructor.

LABORATORY EXERCISE

1. With the power off, examine the scope and locate the following controls or their equivalents.

   a. INTENSITY

   b. FOCUS

   c. VERTICAL INPUT TERMINALS

   d. VOLT/CM

   e. TIME/CM

   f. SYNC controls or

   g. TRIGGER controls

2. a. Find out, from the operating manual, how to turn off the internal sweep. This may be done by setting the TRIGGER LEVEL to a high position, or by turning the sweep selector to external (with no external input signal).

   b. Turn the FOCUS and INTENSITY controls fully counterclockwise.

   c. Set the VERTICAL and HORIZONTAL POSITION controls to the midpoints of their positions.

   d. Turn on the scope and allow it to warm up for at least one minute.

   e. Turn up the intensity until you see a spot on the screen. Do not turn the intensity higher than you need to. A glow around the spot indicates a too-high intensity. If no spot is visible, it is probably "off-screen." Use the positioning controls to move the spot onto the screen.

   f. Rotate the FOCUS control to see

the effect, and adjust to get a very small bright dot on the screen.

g. Observe the effects of the HORIZONTAL and VERTICAL position controls and center the dot.

h. Set the SWEEP selector to an internal sweep and turn on a recurrent sweep. You will need to consult the operating instructions.

i. Observe the effect of changing the TIME/CM setting. Expand the dot into a line by increasing the sweep rate.

3. You are now ready to observe an input signal.

a. Connect the voltage output of a sine and square-wave generator to the vertical input of the scope. Connect the ground terminal of the generator to the ground input of the scope.

b. If you have a triggered scope, set the TRIGGER to "auto." If the scope is not triggered, set the SYNC selector to INTERNAL.

c. Set the TIME/CM switch to the slowest sweep rate (on the order of 1 s/cm). (Make sure the vertical is set for *calibrated* measurements.)

d. Set the generator to give a sine wave with a frequency of 1000 Hz. Turn on the generator.

e. Adjust the generator output (and/or VOLTS/CM control) to obtain a signal which is about 5 cm high.

f. Observe the effect of increasing the sweep rate.

g. Observe the effect of varying the frequency of the input signal.

h. Change the output of the generator to "square wave" and observe the pattern.

i. If you have a triggered scope, set the TRIGGER to INTERNAL. Adjust the TRIGGER LEVEL control until you get a stable trace which "stands still." Center the trace.

j. Measure the length of a single pattern on the screen and use the TIME/CM setting to compute the duration of the pattern. How does your measured value compare with the value computed from the known input frequency? (Be sure the *multiplier* is set to 1, or that you include the proper factor.)

k. Change the input frequency and repeat (i) and (j).